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1 Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB
2 Centre for Ecology and Hydrology, Monks Wood, Abbots Ripton, Huntingdon PE28 2LS

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Scottish Natural Heritage
Publications Section
Battleby, Redgorton, Perth PH1 3EW
UNITED KINGDOM

Scottish Natural Heritage
Chief Scientist's Unit
2 Anderson Place, Edinburgh EH6 5NP
UNITED KINGDOM

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SUMMARY

The exposure of plants, soils and freshwaters throughout Scotland to the major air pollutants has been quantified in this study. The "critical loads and levels approach" is used to compare measured and modelled concentrations and depositions of sulphur compounds, nitrogen compounds and ozone with ecosystem sensitivity.

The definition of **critical load** as adopted by the United Nations Economic Commission for Europe (UNECE) is "a quantitative estimate of exposure to one or more pollutants below which significant harmful effects on sensitive elements of the environment do not occur according to present knowledge". For exposure to gaseous pollutants, the term **critical level** is used, which is defined as "the concentrations in the atmosphere above which direct adverse effects in receptors such as plants, ecosystems or materials, may occur according to present knowledge".

This is the first time that maps of critical loads and levels exceedance for habitats and species in Scotland have been constructed. The relationships between mapped critical load exceedance and actual damage have not been established quantitatively and therefore the exceedance of critical loads or levels should be interpreted as indicating the *potential* for environmental damage and not as actual damage. The maps provide a focused picture of where damage may be occurring from air pollution in relation to nature conservation concerns. The following outline the main results.

- **Critical loads - acidification**: current acidifying inputs in Scotland indicate that exceedances of critical loads for acidification occurs across all habitats with the extent ranging from 53% of the 1km squares in which coniferous woodland occurs, to 87% of the 1 km squares in which peatland occurs.

- **Critical loads - eutrophication**: current atmospheric inputs of nitrogen in Scotland exceed the critical load for eutrophication in six of the seven habitats investigated. The largest exceedances were for coniferous and deciduous woodlands (75-76% of 1km squares in which they occurred) and oligotrophic waters (65%). Only 2% of the 1km squares in which acid grassland occurred received deposits in excess of their critical load whereas critical loads for calcareous grasslands were not exceeded

- **Critical levels - ozone**: current exposure to ozone exceeds critical levels for crops and semi-natural vegetation across 49% of Scotland, largely in the uplands.

- **Critical loads and levels for a number of selected species:** individual species exceedances of critical loads and levels have been quantified for *Calluna vulgaris, Drosera rotundifolia, Racomitrium lanuginosum* and *Primula* spp. Exceedances of acidifying and eutrophying inputs mainly occur in the lowlands and usually near conurbations.

1. INTRODUCTION

The deposition of acidifying and eutrophying pollutants as gases (SO_2, NO_2, HNO_3, NH_3) and as SO_4^{2-}, NO_3^-, NH_4^+ and H^+ in precipitation and aerosols has been shown to lead to acidification of terrestrial ecosystems in Europe and North America (Grennfelt *et al.,* 1995). The ecosystem effects of acidification range from changes in biodiversity of freshwater fauna to direct effects on the physiology of forest trees. Many of the more subtle, longer term effects are associated with changes in the underlying biogeochemical cycling of key elements. A detailed consideration of these underlying processes is outside the scope of this document and the reader is referred to review documents such as CLAG (1994) and Grennfelt *et al.* (1995) to provide the necessary background.

This report provides an assessment of the exposure of terrestrial ecosystems in Scotland to these major pollutants. A recent assessment of UK pollutant deposition and effects has made it possible to provide an improved resolution of the data to a 5 km x 5 km scale and to include greatly improved estimates of current deposition.

In the case of Scotland, there are particular features of the geography and ecology which are important in considering the effects of acidifying or eutrophying air pollutants. Firstly, the climate and geography leads to very large inputs of rain on the mountains of western Scotland, and a steep gradient in the quantity of precipitation from the west to the east. The high rainfall leads to relatively large inputs of any pollutants which are readily removed from the atmosphere by rain and snow, and this includes the soluble aerosol phase SO_4^{2-}, NO_3^-, NH_4^+ and H^+ (as well as ions of marine origin).

Secondly, the geographical position of Scotland on the north western boundary of Europe, leads to a contrast between trajectories of air from 'clean' marine areas to the west and north over the Atlantic, and air trajectories from the east and south, where the main sources of pollutants are found. These features lead to marked geographical gradients in the concentrations of the long-range transported pollutants (SO_4^{2-}, NO_3^-, NH_4^+ and H^+ and O_3), with the largest concentrations in the east and south and the smallest concentrations in the north and west. However, the large rainfall on the uplands of the central and western highlands compensates for smaller concentrations, and wet deposition of all ions is at a maximum in these areas. Thus in Scotland the areas of largest deposition are, in general, areas with small emissions of the primary pollutants.

The remaining characteristic of Scotland, which is essential to consider when determining the impact of air pollutants, is the underlying geology and the soils derived from it. Scotland has large areas of slowly weathering parent minerals which are very sensitive to acid inputs. Thus deposited acidity may readily remove base cations and acidify soils which weather slowly and therefore recover slowly from the effects of acidification. The ecology of the remote west, north and upland areas since the last glaciation has developed in a cool, wet climate with small atmospheric inputs of fixed nitrogen. The pollutant emissions which are largely restricted to the last 100-150 years have therefore added large quantities of acidity, sulphur and nitrogen to ecosystems with a very limited inventory of major nutrients.

1.1 Critical loads and levels

The methods developed in Europe to assess the potential effects of acidifying and eutrophying pollutants rely largely on the **critical loads** approach. The definition of **critical load** as adopted by the United Nations Economic Commission for Europe (UNECE) is "a quantitative estimate of exposure to one or more pollutants below which significant harmful effects on sensitive elements of the environment do not occur according to present knowledge". The term critical load refers only to the deposition of pollutants. For exposure to gaseous pollutants, the term **critical level** is used, which is defined as "the concentrations in the atmosphere above which direct adverse effects in receptors such as plants, ecosystems or materials, may occur according to present knowledge".

Areas of differing critical loads and levels may be shown on maps. These allow the physical, chemical and geological sensitivities to pollutants to be combined and quantified spatially. When maps of environmental sensitivity to pollutants are developed as critical loads maps, these may be compared with maps of deposition of the pollutant (acidifying or eutrophying) in order to define areas of exceedance of the critical loads. These critical loads exceedance maps, of which many are presented here, are not maps showing the magnitude of effects, they are simply maps showing where the potential for these effects may be located. Similarly, for critical levels the critical levels exceedance maps show where the potential for effects may be found.

2 DEPOSITION

2.1 Acid deposition including NH_3 (and NH_4^+)

The deposition of acidifying pollutants comprises wet deposition of SO_4^{2-}, NO_3^-, NH_4^+, and the dry deposition of SO_2, NO_2, HNO_3 and NH_3 and aerosol SO_4^{2-}, NO_3^- and NH_4^+. Their depositions have been mapped at a spatial resolution of 5 km by 5 km, weighted within each grid square by the proportion of various land covers, as deposition rates differ according to the vegetative structure, e.g. deposition rates on forests exceed rates for short vegetation for the reactive pollutants and aerosols (Fowler *et al.,* 1991). Figure 1 shows the map of total annual acid deposition throughout Scotland at a 5 km x 5 km resolution. The averaging period of 1995-1997 is used to show the current deposition rates without the inter-annual confounding effects of weather. To place these data in the geographical context of the whole UK, an inset figure is provided. This shows that the range of acid deposition in Scotland is similar to that in the rest of the UK, but the areas with small inputs (< 0.7 keq ha^{-1} $year^{-1}$)[1] predominantly occur in Scotland. The inset figure also shows that the area of greatest deposition (> 2 keq ha^{-1} $year^{-1}$) in Scotland is small relative to extensive areas in the Pennines, Cumbria, Wales and South West England where deposition rates exceed 2 keq ha^{-1} $year^{-1}$.

2.2 Acid deposition excluding NH_3 (and NH_4^+)

The potential for NH_3 and NH_4^+ deposition to acidify is well established (Sutton *et al.*, 1993; Binkley and Richter, 1987). However, the fate of deposited NH_3 and NH_4^+ must be defined to know the degree to which deposition of reduced N is acidifying. The deposition of NH_3 and NH_4^+ may represent a substantial fraction of the potential acidifying input in many areas, and it is therefore important that maps of acidifying pollutants are also presented without the reduced nitrogen components. Figure 2 presents the acidifying inputs for the average of 1995-1997 excluding NH_3 and NH_4^+.

The immediate effect of reduced nitrogen is clear with only three 5 km x 5 km grid squares receiving more than 2 keq ha^{-1} $year^{-1}$ when reduced nitrogen (NH_x) is excluded from the map. The deposition of reduced nitrogen is therefore a major part of the potentially acidifying input, and the uncertainty over the fate of the deposited nitrogen in this form represents one of the largest uncertainties in the overall acidification picture.

[1] The unit keq ha^{-1} $year^{-1}$ refers to the mass of acidity deposited in thousands of equivalents per hectare per year

2.3 Nitrogen deposition

The degree of eutrophication includes the total deposition of both oxidised (NO_y) and reduced (NH_x) nitrogen. Although it has often been pointed out that the extent of eutrophication effects per molecule of N from NO_y and NH_x may differ (e.g. Hornung *et al.*, 1995), because of the uncertainties in making this distinction it is generally assumed that they contribute similarly to impacts, which are scaled against total N input. The overall budget of nitrogen deposition to Scotland is shown in Figure 3. This indicates the highest rates of nitrogen deposition occur mainly in hill areas of the south west, the Borders, the west, and also across Grampian. This particularly corresponds to large inputs by wet deposition of NH_4^+ and NO_3^- of the high rainfall areas of the west. The high ground in north west Scotland and the Hebrides also receives a large annual precipitation, but the concentrations of nitrogen compounds in rain in these areas is small.

The rates of NH_3 deposition are highly dependent on land type. This is because many agricultural ecosystems emit NH_3, while NH_3 is most effectively deposited to forests. For this reason, critical loads for nitrogen eutrophication need to be matched to deposition estimates for the appropriate habitats. To illustrate the importance of this, we show the corresponding maps of total nitrogen deposition that would be received by forests and heathland across Scotland (Figures 4 and 5). These maps show what would be deposited to each habitat type if it were present in a grid 1 km square. Firstly, it should be noted that the inputs to forest are larger than for heathland/rough grazing. Secondly, both estimates are much larger than the average inputs to 5 km grid squares (Figure 3). The spatial pattern is also different, particularly for forests due to a larger contribution to deposition from gaseous NH_3. Hence Figure 4 shows the largest deposition occurring in lowland areas of Scotland, in the north east, central belt and south west Scotland. In both Figures 4 and 5, the inputs are generally less than in many areas of England and Wales. However, there are significant 'hot spots' which are comparable with the peak values of the UK. In addition, in terms of ecological effects, nitrogen deposition patterns in Scotland occur where large areas of ecosystems are very sensitive to nitrogen deposition. This is shown in Section 5.

2.4 Ozone deposition

Ozone is included in this study as this phytotoxic gas is currently the gaseous pollutant which exposes the largest area of semi-natural vegetation in Scotland to potentially damaging concentrations. Furthermore, unlike the other pollutants, the concentrations of ozone are predicted to increase over the next 50 years.

Ozone at terrestrial surfaces has two sources, first a minor contribution from the stratosphere and a second much larger contribution by photo-chemical production within the troposphere from the pollutants NO_x and volatile organic compounds (PORG, 1998). The current threat to vegetation is largely through exposure to concentrations sufficiently large to damage physiological processes of plants, often in the absence of visible injury. These large concentrations arise in plumes of polluted air from the industrial areas of Europe which are drawn over Scotland by larger scale weather systems. These concentrations typically occur in anticyclonic, sunny conditions which permit the photochemical production of ozone while the air is transported. Thus elevated and damaging concentrations may occur 1,000 km downwind of major source areas.

To provide a measure of the potential for O_3 effects on vegetation, the AOT40 index has been developed. The AOT40 is simply the sum of the exposure in ppb multiplied by the number of hours above 40 ppb, i.e. a concentration of 50 ppb of O_3 for an hour would contribute 10 ppb hours to the AOT40 at the site in question. Experimental studies have allowed critical levels for O_3 exposure to be defined for crop and semi-natural vegetation (3,000 ppb hours over 3 months April-July), and for forest (10,000 ppb hours over 6 months April-September).

Concentrations of O_3 exceed 40 ppb in sunny, warm conditions, whenever trajectories of air upwind of Scotland cross the major source areas of O_3 precursors (i.e. volatile organic compounds and NO_x). Thus O_3 concentrations occasionally exceed 40 ppb, a value above which potential for effects of O_3 on sensitive vegetation has been demonstrated in controlled conditions (PORG, 1998).

3 EMPIRICAL CRITICAL LOADS OF ACIDITY FOR SCOTTISH SOILS

The empirical critical loads map for Scottish soils has been developed following the methods described at the 1988 Skokloster workshop and is based on the dominant weatherable soil minerals (Nilsson and Grennfelt, 1988). For soils, critical loads may be regarded as the maximum acidic deposition that can be deposited onto soil without changing the acidity of the soil. Critical loads were therefore assigned to each of the soil classes according to the amount of acidity which would be neutralised by the production of base cations from weathering. In the case of peat soils, which are widely distributed in Scotland, the critical loads are derived from studies of the relationships between rainfall chemistry and equilibrium pH. These led to the critical load being determined by the input of H^+ and Ca^{2+} which would not result in a pH change within the peat of greater than 0.2 pH units (Burton and Hodgson, 1987; Smith *et al.*, 1993).

The map of critical loads for soils in Scotland shows that soils with small critical loads are distributed widely in Scotland (Figure 6). In particular, the most sensitive soils (coloured black) are common in the South West, notably Galloway, on Islay and Jura, in the central Highlands, in Caithness, Sutherland, and on Shetland. These soils occupy 7.3% of the land area. The next most sensitive soil class, 0.25–0.5 keq ha^{-1} (coloured red), is the most common class in Scotland covering 59% of the land area. In contrast, England has large areas of calcareous soils which are insensitive to acidic inputs.

The map is presented at a spatial resolution of 1 km x 1 km by allocating each square to a critical load class on the basis of the mineralogy of the dominant soil unit.

4 POLLUTANT DEPOSITION ON HABITATS

4.1 Introduction

In order to construct maps to indicate where pollution deposition or air concentrations of pollutants may be potentially damaging to habitats of nature conservation interest, it was necessary to construct maps on the distribution of habitats. In the absence of survey data, national biogeographic and autecological databases on species' distributions and the habitat requirements of species were used to identify potential distributions of habitats across Scotland.

The CEH Biological Records Centre (BRC), Britain's biodiversity data centre, has gathered information on species distribution since its foundation in 1964 (Harding and Sheail, 1992). BRC data are geo-referenced using the Ordnance Survey (OS) grid, and post-1980 data generally have a spatial resolution of 100 m. In the present study, the 10 km squares of the OS grid were used, since this is a convenient presentational and analytical scale, with 1121 sampling units in Scotland. Some degree of patchiness (recorder bias) is inevitable since data come largely from volunteer recorders (Prendergast *et al.*, 1993).

In addition to species-distribution data, BRC has also developed the Biotope Occupancy Database (BOD) which details habitat associations for a range of plant and animal species (Griffiths *et al.*, 1999). The BRC information and the BOD can be used in a two-stage process to define the spatial extent of habitats:

1. *Linking species and habitats.* The BOD is used to define characteristic species for each habitat type (Section 4.2).

2. *The potential distributions of each habitat type.* The distributions of individual species characteristic of a habitat are overlaid. OS grid squares with the greatest number of species are presumed to indicate the presence of that habitat (Section 4.3).

4.2 Defining characteristic species for each habitat type

The Biodiversity Broad Habitat Classification was developed as part of the UK Biodiversity Action Plan (UK Biodiversity Steering Group 1995; UK Biodiversity Group,1998 and 1999). It provides a comprehensive framework for the surveillance of the UK countryside. We used this classification to identify habitat types for which sets of characteristic plant species can be defined. Jackson (2000) defines relationships between the BAP Broad/BAP Priority habitat types and other classifications such as National Vegetation Classification (NVC) communities and Countryside Survey (CS) 1990 reporting classes for which available datasets exist. Whilst an attempt to define the habitat distributions using the BAP Priority Habitat classification was made (since this is the most useful habitat classification for monitoring), data were generally only good enough to provide adequate distributions for the BAP Broad Habitat types (Table 4.1).

Table 4.1: The ten habitat types for which potential distribution maps were produced using the distributional data from component species. The deposition class refers to the general habitat category in which pollutant deposition data are collected (this is explained in Table 4.2). BAP habitats are categorised as 'Broad' (general) habitats within which 'Priority' habits are identified.

DEPOSITION CLASS as used by air pollution specialists	HABITAT TYPES WITH POTENTIAL DISTRIBUTIONS DEFINED in this report	EQUIVALENT BAP HABITAT CATEGORY as defined by the UK Biodiversity Steering Group
Arable	Arable weeds	Arable (Broad) Cereal field margin (Priority)
Bare rock and soil	Sand dunes	Coastal sand dunes (Priority)
Blanket bog	Raised bog and blanket bog	Bogs (Broad)
Coniferous wood	Coniferous woodland	Coniferous woodland (Broad)
Deciduous wood	Deciduous woodland	Deciduous woodland (Broad)
Freshwater	Oligotrophic waters	None
Grassland (unfertilised)	Acid grassland	Acid grassland (Broad)
Grassland (unfertilised)	Calcareous grassland	Calcareous grassland (Broad)
Grassland (unfertilised)	Saltmarsh	Saltmarsh (Broad)
Heathland and rough grazing	{Lowland heathland} {Upland heathland}	Dwarf shrub heath (Broad)

Data on the occurrence of plant species within these habitats were derived from two major data sources: (1) the constancy tables of the NVC (Rodwell 1991a, 1991b, 1992, and 1995) and (2) the quadrat samples collected by Countryside Survey 1990 (Barr *et al.,* 1993). We calculated the frequency of plant species within the ten habitat categories outlined in Table 4.1.

For each species, the observed frequency in a given habitat type, *o*, was compared with its expected frequency in all habitats, *e*. The habitat-specificity, *P*, of a species was graded by its preference index

$$P = \{(o-e) * \text{abs}(o-e)\}/e$$

such that *P* is independent of the number of quadrats per habitat and can be used to compare the degree of preference of species for heavily or less heavily sampled habitats.

Species within each habitat category were ranked by preference value, and assigned to ten bands of habitat-specificity. For consistency between habitat types, species within the top three bands of habitat-specificity were used to define the set of characteristic (habitat-specific) species used to derive the potential distribution of each habitat type.

4.3 Potential distribution of habitat types

4.3.1 Data sources – Biological Records Centre (BRC)

From the foundation of the BRC, data have been used to prepare maps summarising the national distribution of species, which have been published in atlases, taxonomic treatises and studies of individual taxa. Secondly, the data have been used in the preparation of Red Data Books (e.g. Bratton, 1991; Perring and Farrell, 1977; Shirt, 1987; Hodgetts *et al.,* 1996), and national reviews of threatened or uncommon species, including the *UK Biodiversity Action Plan*.

For the present study, data were incorporated from several major BRC sources. Data for vascular plants are those published by Perring and Walters (1962) and Rich and Woodruff (1990), together with extensive updates, particularly for scarce plants (Stewart *et al.,* 1994), rare plants (Wigginton, 1999) and aquatic plants (Preston and Croft, 1996). Data from a major current initiative to produce a new atlas of the British flora, Atlas 2000 (Pearman and Preston, 1996), were not available for this project).

4.3.2 Distribution of habitat types

The potential distribution of habitat types was assessed by co-occurrence mapping of the distribution of constituent habitat-specific species. For example, a given habitat type is likely to occur in a 10 km square which contains a high proportion of its habitat-specific species. Habitat specialists from Scottish Natural Heritage (SNH) were consulted to define appropriate cut-off values to define the extent of habitats. In the current study this method was used to define the habitat distributions in Scotland of arable weeds, raised bog, blanket bog, acid grassland, calcareous grassland, coniferous woodland, deciduous woodland, upland and lowland heathland, oligotrophic waters, saltmarsh and sand dunes. However, restrictions in the availability of deposition data meant that raised and blanket bogs were considered together (as "peatlands") as were upland and lowland heathland (as "heathland") (as outlined in Table 4.1).

This method worked better for some habitats than others for various reasons. For example, more northerly latitudes may have different species mixes and may be less species-rich. This was the case for sand dunes in Shetland. SNH therefore provided additional data for six 10 km grid squares for sand dune habitats in Shetland and a 10 km data set to define the distribution of oligotrophic waters in Scotland, which replaced the one generated using the method above. In addition, the CEH satellite Land Cover Map of Great Britain (Fuller *et al.*, 1994) was subsequently used to improve the definition of the distribution of arable, coniferous and deciduous woodland. This map is based on satellite data and grid squares were included in the distributions where the appropriate land cover classes occupied at least 5% of each 1 km grid square.

4.4 Assigning critical loads to habitats

National critical loads for acidity and eutrophication have been defined for five terrestrial ecosystems called 'deposition classes'. These are: acid grassland, calcareous grassland, heathland, coniferous woodland and deciduous woodland (Hall *et al.*, 1998). In addition, acidity critical loads are calculated for selected freshwaters throughout Great Britain; these sites are lakes or headwater streams with small catchment areas located in the most acid-sensitive regions of each 10 km grid square. However, for the habitats selected to study in this report, it is currently not possible to determine acidity and nutrient nitrogen critical loads for arable crops, sand dunes, freshwater habitats and saltmarsh. Table 4.2 lists the habitats that SNH requested to be included in this study and the availability of appropriate critical loads and levels data. The methods described below for the calculation of acidity and nutrient critical loads are those agreed by UK experts and are consistent with methods given in the UNECE Mapping Manual (UBA, 1996) and applied under the UNECE Convention on Long-range Transboundary Air Pollution.

4.5 Acidity critical loads

Two methods have been used nationally to calculate acidity critical loads for terrestrial ecosystems:

(i) empirical critical loads of acidity for soils: this method is based on the weathering rate of the mineralogy of the dominant soil type in each 1 km square of the UK (Figures 7-10).

(ii) simple mass balance equation: this method is based on balancing all the sources and sinks of acidity within the soil system. In the UK and many countries in Europe this method has been used to determine critical loads of acidity for forest soils (Figures 11 and 12).

For this study, empirical critical loads at 1 km resolution have been applied to the appropriate non-forest habitats, i.e. acid grassland, peatland, calcareous grassland and heathland. These 1 km critical load values have been assigned to each 1 km square within each 10 km square within which the habitat occurs. The simple mass balance equation, parameterised separately for coniferous and deciduous woodland, has provided the acidity critical loads for the 1 km habitat areas from the CEH Land Cover Map.

4.6 Nutrient nitrogen (eutrophication) critical loads

Excess nitrogen deposition can contribute to both acidification and eutrophication of soil and surface waters. As for acidity, there are two methods that can be used to determine nutrient nitrogen critical loads:

(i) empirical approach, where critical load values are set on the basis of field observations or experiment or published data on the changes in the structure or function of ecosystems;

(ii) mass balance approach, where the critical load allows for nitrogen sinks (immobilisation in the soil, uptake by plants, denitrification) and an acceptable amount of nitrogen leaching. This method can be used to determine nutrient nitrogen critical loads for forest ecosystems (Figures 13 and 14).

Ranges of empirical critical load values have been defined for 19 different ecosystems (UBA, 1996). Within those ranges, UK experts have agreed on appropriate individual values for UK ecosystems (Hall *et al.*, 1998). This approach has been used in this study to set critical loads for acid grassland, peatland, calcareous grassland, heathland and oligotrophic waters (as outlined in Table 4.2). The single critical load value is assigned to each 10 km square in which the habitat potentially occurs.

For coniferous woodland, critical loads were calculated using the mass balance equation. For deciduous woodland, critical loads were determined using both approaches and minimum of the two applied. For both woodland habitats, the critical loads were assigned to each 1 km square of the habitat as defined from the CEH land cover map.

Table 4.2. Habitat distributions that have been defined and the associated critical loads that can be assigned to those habitats. Deposition class refers to the general habitat category in which pollutant deposition data are collected. Shading indicates that maps of exceedances for these habitats are presented in section 6 of this report.

Deposition Class	✓ = Habitat Distribution Defined (habitats originally agreed to consider are shown in bold)	Data Used To Define the Habitat Distribution	Acidity Critical Load	Nutrient Nitrogen Critical Load	Critical Level For Ozone
Arable	Arable weeds (✓)	Biotope Occupancy Database (BOD)	None	None	Yes
	Arable crops	CEH satellite Land Cover Map	None	None	Yes
Bare rock and soil	**Sand dunes (✓)**	BOD and SNH data	None	None	
	Shingle/rocks/cliffs	Cannot be defined from BOD or the CEH satellite Land Cover Map	None	As for bryophytes and lichens	
	Limestone pavements				
	Scree				
Peatland	**Raised bog and blanket bog (✓)**	BOD	Empirical	Empirical - 10 kg N/ha/year	
Coniferous wood (✓)	Planted conifers	Coniferous woodland defined from the CEH satellite Land Cover Map	Simple Mass Balance	Mass Balance	
	Native Pine (Caledonian)				
Deciduous woodland (✓)	**Oak**	Deciduous woodland defined from CEH satellite Land Cover Map	Simple Mass Balance	Minimum (mass balance, empirical)	
	Beech				
	Ash				
	Birch				
	Lowland wood				

Deposition Class	✓ = Habitat Distribution Defined (habitats originally agreed to consider are shown in bold)	Data Used To Define the Habitat Distribution	Acidity Critical Load	Nutrient Nitrogen Critical Load	Critical Level For Ozone
Freshwater	Mesotrophic standing waters	Cannot be defined from BOD or the CEH satellite Land Cover Map	None	None	
	Eutrophic standing waters				
	Aquifer-fed waterbodies				
	Rivers and streams		Specific sites only	None	
	Oligotrophic standing waters (✓)	SNH data	None	Empirical - 7.5 kg N/ha/year	
Grassland	Improved grass	Distribution not defined	None	None	
Grassland (unfertilized)	Unimproved hay meadow	Distribution not defined	Empirical	Empirical - 50 kg N/ha/year	
	Acid grassland (✓)	BOD	Empirical	Empirical - 25 kg N/ha/year	
	Calcareous grassland (✓)	BOD	Empirical	Empirical - 50kg N/ha/year	
	Machair	Distribution not defined	None	None	
	Saltmarsh (✓)	BOD			
	Arable field margins	Distribution not defined			
Heathland and rough grazing	**Lowland heathland (✓)**	BOD (lowland and upland heathlands together)	Empirical	Empirical - 17 kg N/ha/year	
	Upland heathland (✓)				
	Alpine and sub-alpine heaths	Distribution not defined	Empirical	Empirical - 10 kg N/ha/year	
	Grazing marsh	Distribution not defined	None	None	
	Alkaline fens and reedbeds	Distribution not defined			

5 CALCULATING CRITICAL LOAD EXCEEDANCES ON HABITATS

An exceedance is defined as the amount of pollutant deposition above the critical load. The deposition data used are the latest available mean data for 1995-97 at a 5 km resolution. Deposition to different habitat types can be very different, for example, trees capture more deposition than low growing vegetation. Therefore, deposition values for low-vegetation were used to calculate exceedances of the non-woodland ecosystems and separate deposition values specifically for woodlands were applied in the calculations of exceedance of critical loads for coniferous and deciduous woodland.

5.1 Exceedance of acidity critical loads

In calculating exceedance of acidity critical loads, acid deposition is defined as

Acid-dep = (NMS + net N deposition) – net base cation deposition

Where *NMS* = non-marine sulphur deposition,

net N deposition = oxidised N – $(N_{uptake} + N_{immobilisation})$, and

net base cation deposition = *NMBC* – BC_u; *NMBC* is the non-marine base cation (calcium + magnesium) deposition and BC_u is the base cation uptake (removal by harvest).

The following points should be noted:

(i) Uptake values for nitrogen and base cations are ecosystem specific.

(ii) Nitrogen immobilisation values are determined by soil type at 1 km resolution.

(iii) Non-marine base cation deposition are based on the same datasets as used to calculate the maximum critical load of sulphur when the Critical Loads Function is used to calculate exceedances (Hall *et al.*, 1998; Hall *et al.*, in prep.). This ensures that the exceedance values calculated using acid deposition (as defined above) are the same as would be calculated using the Critical Loads Function. The results are then also consistent with work carried out under the Convention on Long-Range Transboundary Air Pollution (CLRTAP) where, by necessity, base cation deposition is an integral part of the critical loads calculations, since European scale base cation deposition data are not available.

(iv) There is uncertainty associated with the role of reduced nitrogen (ammonia) deposition in acidification. For this study it has not been included in the calculations of exceedance of acidity critical loads.

The exceedance is calculated by subtracting the acidity critical load value from the acid deposition value on a grid square basis. As 1 km resolution acidity critical loads data were assigned to each of the habitats, exceedances were also calculated at 1 km resolution by assuming the deposition values of non-marine sulphur and oxidised nitrogen remain constant across each 5 km grid square. To calculate exceedances at the same resolution as the deposition data (i.e. 5 km) would require the use of a statistic for both the 1 km critical loads and nitrogen immobilisation data.

5.2. Results of mapping critical loads exceedances for acidity

Maps of the exceedances of acidity critical loads for the various habitats are shown in Figures 15 to 20, and the results summarised in Table 5.1.

Table 5.1. The number and percentage of 1 km grid squares where acidity critical loads are either exceeded or not exceeded.

HABITAT	NUMBER AND PERCENTAGE OF 1 KM SQUARES	
	Exceeded	Not exceeded
Peatland (bog)	36,176 (88.1%)	4,866 (11.9%)
Calcareous grassland	3,160 (87.5%)	453 (12.5%)
Acid grassland	33,155 (87.4%)	4,774 (12.6%)
Heathland	24,488 (63.3%)	14,187 (36.7%)
Deciduous woodland	2,863 (61.7%)	1,780 (38.3%)
Coniferous woodland	7,293 (52.6%)	7,143 (47.4%)

5.3 Exceedance of nutrient nitrogen critical loads

Both oxidised and reduced nitrogen depositions contribute to eutrophication and therefore both are included in the calculation of exceedances of critical loads for nutrient nitrogen. Exceedance is calculated as

Exceedance = (oxidised + reduced N deposition) – critical load for nutrient nitrogen

Where the habitat distributions have been defined at 10 km resolution from species data, the single critical loads value is applied to each 10 km grid square (see above). However, as the deposition data are at 5 km resolution, exceedances were also calculated at 5 km resolution by assuming the presence of the habitat and the same critical load value for each 5 km square within each 10 km habitat distribution square. The woodland habitat distributions and critical loads were defined at 1 km resolution, so exceedances were also calculated at 1 km resolution using the same method as applied for exceedances of acidity critical loads.

5.4 Results of mapping critical loads exceedances for nutrient nitrogen

Maps of the exceedances of nutrient critical loads are shown in Figures 21 to 27, and the results summarised in Table 5.2.

Table 5.2. The number and percentage of 1 km grid squares where nutrient nitrogen critical loads are either exceeded or not exceeded.

HABITAT	NUMBER AND PERCENTAGE OF 1 KM GRID SQUARES#	
	Exceeded	Not exceeded
Coniferous woodland	11,768 (76.1%)	3,691 (23.9%)
Deciduous woodland	9,386 (74.6%)	3,193 (25.4%)
Oligotrophic waters	32,500 (65.1%)	17,425 (34.9%)
Peatland (bog)	22,125 (44.6%)	27,500 (55.4%)
Heathland	10,325 (19.1%)	43,800 (80.9%)
Acid grassland	1,400 (1.9%)	70,800 (98.1%)
Calcareous grassland	0 (0.0%)	7,975 (100.0%)

#

The total number of 1 km squares for each habitat differs between the acidity maps and the nutrient nitrogen maps for two reasons:

(i) The acidity critical load and exceedance maps are based on where we hold 1 km acidity critical loads data, which for Scotland excludes some areas of water, for example lochs. Whereas, the nutrient nitrogen maps (for non-woodland ecosystems) consist of a single critical load value applied to all 1 km squares within each 10 km square identifying that habitat. Therefore, the total 1 km square count for the nutrient nitrogen maps is greater than that for the acidity maps.

(ii) Although the CEH Land Cover Map was used to define coniferous and deciduous woodland areas, there are still differences in the total numbers of 1 km squares defining the habitat for acidity and for nutrient nitrogen, because of differences in the availability of data for calculating both acidity and nutrient nitrogen critical loads.

6 POLLUTANT DEPOSITION IN RELATION TO CHANGING DISTRIBUTIONS OF INDIVIDUAL SPECIES

6.1 Selecting species to indicate distributional changes in relation to pollutant deposition

The detrimental effect of atmospheric pollution on the distribution of certain species groups is well known, e.g. for lichens, mosses and liverworts. It was important to chose species that are not too common at the 10 km^2 scale since effects may be manifested through changes in abundance rather than presence or absence at that scale, or to choose species that are affected only at the sub-lethal level, e.g. trees may experience reduced growth rather than disappear from a 10 km^2 in the case of high pollution levels. Distribution data for selected moss species were therefore used to determine whether trends in declines are correlated with temporal trends in pollutant levels. It is not yet possible to detect any recovery of original distributions with falling pollution levels.

Moss distribution data were taken from Hill *et al.* (1991, 1992, 1994). The seven selected species below are all believed to be susceptible to atmospheric pollution, especially SO_2, and are known to have declined in certain areas of Scotland.

1 *Antitrichia curtipendulas* is found on rocks and boulders, scree, cliffs, walls, and epiphytic on a range of trees and scrubs. It had disappeared from most areas in the southeast of the UK before 1900, almost certainly due to SO_2 pollution.

2 *Cryphaea heteromalla* is epiphytic, occurring on bare bark or through a thin mat of pleurocarpous mosses on the trunks, branches and occasionally the exposed roots of trees and shrubs, mainly on elders. It favours sheltered and humid conditions,

such as woodlands, shaded rock, concrete and masonry etc. It occurs in the lowlands and is believed to be pollution sensitive since it is less frequent in areas with high SO_2 levels.

3 *Grimmia orbiculare* occurs on exposed dry rocks, especially carboniferous limestone, and walls. Its distribution has been decreasing except in western Britain, which may therefore be a response to atmospheric pollution.

4 *Leucodon sciuroides* is primarily epiphytic, occurring in open sites such as roadsides, hedges and parks. It also occurs on walls and tombstones. It has declined in lowland England due to SO_2 pollution and eutrophication of bark.

5 *Orthotrichum speciosum* is epiphytic, occurring on branches of old hazel and juniper shrubs, and on trunks and branches of trees. It was possibly eliminated from southern British sites by atmospheric pollution but because it has been found recolonising woodlands in the Dutch polders, it might be expected to reappear in eastern England and the Scottish Lowlands following recent reductions in SO_2 levels.

6 *Ulota coarctata* is an epiphyte that forms small yellowish or dark green tufts on trees and bushes in sheltered humid places in lowland areas.

7 *Ulota hutchinsiae* occurs on dry or intermittently flushed rocks and boulders, rarely on trees.

6.2 A method relating temporal changes in moss distributions to pollution levels

Atmospheric concentration data from urban and rural air pollution networks were combined to provide maps of SO_2 levels for the last four decades. The earliest data available for urban areas date from 1962/63. Data also existed for 1970/71, 1980/81 and 1990/91. The earliest available modelled rural concentration fields exist for 1987-1991. As rural concentrations of air pollutants in Scotland are believed to have remained relatively stable over these four decades, the rural concentrations were averaged across 1987-1991 and this average was combined with the urban data across the four decades.

The temporal trends in SO_2 concentrations from 1962/63 to 1990/91 show large decreases for urban areas shown by the change from red to orange in Figure 28. The colour circles within Figure 28 indicate the results from the rural network. Changes in the distributions of the selected mosses over two time periods (pre-1950 and 1950 onwards) are shown in Figures 29-35, combined with the SO_2 concentration estimates for 1962/63, the most polluted period.

6.3 The results

The distributions of the mosses occur mainly within the lowest bands of SO_2 concentrations (Table 6.1). They are absent from the most populated areas of Scotland (Figures 29-35). However, the distribution data have not been collected on a consistent basis over the century and so it is difficult to detect re-appearance of species, i.e. there are 10 km squares where species occurrences were recorded post-1950 but not pre-1950. Absences pre-1950 may have occurred because recording was very patchy in this period. Disappearance (i.e. pre-1950 occurrence, but not post-1950) is genuine, however, and can be related to pollution. The loss of mosses from 10 km squares has occurred mainly in the higher bands of pollution and their post-1950 range has contracted to northern parts of Scotland.

Table 6.1. The distribution of selected moss species according to differing SO_2 concentrations (g m^{-3}). The colours refer to the bands of SO_2 concentration in Figures 29 to 35. Figures are the number of 10 km squares where the moss has been recorded - All records = recorded before and after 1950; Losses = not recorded since 1950.

SO_2 concentration µg m^{-3}	*Antitrichia curtipendula (Figure 29)*		*Cryphaea heteromalla (Figure 30)*		*Grimmia orbiculare (Figure 31)*	
	All records	Losses	All records	Losses	All records	Losses
0-5 (blue)	108	10	10	2	2	2
5-10 (green)	47	36	57	10	4	2
10-20 (yellow)	4	9	13	6	0	3
20-40 (orange)	0	0	0	0	0	1
> 40 (red)	1	1	0	1	0	2
Total	160	56	80	19	6	10

SO_2 concentration µg m^{-3}	*Leucodon sciuroides (Figure 32)*		*Orthotrichum speciosum (Figure 33)*		*Ulota hutchinsiae (Figure 34)*		*Ulota coarctata (Figure 35)*	
	All records	Losses	All records	Losses	All records	Losses	All records	Losses
0-5 (blue)	17	7	9	2	118	4	12	6
5-10 (green)	25	20	10	3	16	10	4	11
10-20 (yellow)	3	8	0	0	1	2	0	0
20-40 (orange)	0	0	0	0	0	0	0	0
> 40 (red)	1	1	0	0	0	0	0	0
Total	46	36	19	5	135	16	16	17

6.4 Discussion

These results provide indirect evidence that pollutant effects may cause declines in the distributions of certain moss species. Any effect of pollution, either acidity or eutrophication, could act directly on the moss or indirectly through effects on other species such as vascular plants. For example, nutrient-enrichment through nitrogen pollution could increase growth of co-occurring vegetation to the detriment of mosses. Also, we cannot exclude other factors that may cause decline in these mosses such as habitat loss and degradation and/or climate change.

The analyses of changes in distribution have been restricted to mosses. However, a major new atlas of vascular plants distributions, Atlas 2000, will allow temporal change for plants in three periods (pre-1950, 1950-1970, post-1970) to be investigated, and may highlight both disappearance and recovery.

7 CONCENTRATIONS OF GASEOUS POLLUTANTS - CRITICAL LEVELS AND EXCEEDANCES

7.1 Sulphur Dioxide (SO_2)

Current concentrations of SO_2 in Scotland are small relative to those of the 1960s, and only close to the large conurbations do the values exceed 10 g m^{-3}. The concentrations are also small compared with the east Midlands of England (Figure 36). Critical levels are listed in Table 7.1.

Table 7.1: Critical levels for SO_2 agreed in 1988 and 1992

Receptor	**Bad Harzburg - 1988** (UBA, 1988)	**Egham - 1992** (Ashmore and Wilson, 1994)
Agricultural crops	70 µg m^{-3} 24 h mean 30 µg m^{-3} annual mean	30 µg SO_2 m^{-3} annual and winter* means
Forests and natural vegetation	70 µg m^{-3} 24 h mean 30 µg m^{-3} annual mean	20 µg SO_2 m^{-3} annual and winter* means 15 µg SO_2 m^{-3} annual and winter means where accumulated temperature sum above 5°C is <1000 degree days per year
Cyanobacterial lichens	-	10 µg SO_2 m^{-3} annual mean

* October-March inclusive

Critical level exceedance maps are presented for crops, forests and semi-natural vegetation and for cyanobacterial lichens. For crops there are no exceedances of the critical levels and in just one 5 km x 5 km square the SO_2 concentration exceeds 75% of the critical level (Figure 37). For forests and semi-natural vegetation, there is one 5 km square exceeded in West Lothian and 4 grid squares which are close to exceedance. As SO_2 concentrations are continuing to decline it is very likely that there will be no exceedances of the SO_2 critical level for this habitat within the next 2 or 3 years (Figure 38).

Finally, the very SO_2 sensitive cyanobacterial lichens show rather more exceedances, with 23 5 km squares, but the total area amounts to just 0.6% of Scotland. These exceeded areas are largely in the central lowlands, but with additional areas around Stranraer and Aberdeen (Figure 39).

7.2 Nitrogen Oxides (NO_x)

Concentrations of NO_x are larger than those of SO_2, reflecting the changes in major sources in the last few decades. In particular the influence of motor vehicles is clear in the concentration field (Figure 40). The absolute values in the lowlands are generally in the range 5 to 15 g m^{-3} with much smaller concentrations in the rural areas and especially the north and north west. By contrast, the concentrations of NO_x in England are very much larger and extend over the whole of England except Wales, the South West, Cumbria and Northumberland.

There is just one critical level for all habitats and this is currently set at 30 g m^{-3} as an annual mean value (Ashmore and Wilson, 1994). There are too few data to justify different critical levels for different ecosystems or species at present. This critical level is exceeded in just 5 of the 5 km grid squares, centred on the city centres of Glasgow, Edinburgh and Aberdeen. There is some evidence of the effects of large roads on the concentration field, and very close to some of these roads, the critical levels may be exceeded, however, with the 5 km resolution, such effects are sub-grid in scale and are therefore not visible in this analysis (Figure 41).

7.3 Ammonia (NH_3)

Concentrations of NH_3 are very spatially variable, reflecting the diffuse nature of the largely agricultural sources and the very short atmospheric lifetime. The concentrations range from 0.1 to 8 g m^{-3}, with the largest concentrations in the lowland areas (Figure 42). The values here are the results from the FRAME (Fine Resolution Ammonia Exchange) atmospheric transport model and these have been compared elsewhere with results from the National Ammonia Monitoring Network.

The critical levels for ammonia are shown in Table 7.2. Compared with the air concentration estimates for Scotland, there is no 5 km grid square in which the annual critical level is on average exceeded. However, as shown in Figure 43, the annual concentration at many sites is a large fraction of the critical level. It should be noted that Table 7.2 also provides monthly and daily critical level values. Although detailed mapped data are not available, an analysis of detailed high-resolution monitoring (Burkhardt *et al.*, 1998) has shown that where the annual critical level is not exceeded, it is highly unlikely that any shorter term critical level for NH_3 will be exceeded.

Table 7.2: Critical levels for ammonia ($\mu g\ m^{-3}$) (CLAG, 1996). For NH_3, the critical levels for all vegetation have been set during UNECE workshops in 1988 and 1992, representing the most recent updates of critical levels.

Averaging Time	Bad Harzburg - 1988 UBA (1988)	Egham - 1992 Ashmore and Wilson (1994)
1 day	600	270
1 month	100	23
1 year	-	8

The lack of exceedance for the NH_3 critical level at a 5 km resolution is because NH_3 is a primary pollutant with ground level sources that shows very high spatial variability. Hence concentrations decrease rapidly away from sources with the result that at a 5 km level it is unlikely for exceedance to occur. By contrast, this local effect also means that exceedance of the critical level is expected at many locations in Scotland in the vicinity of sources (e.g. <300 m distance). This effect however is not shown on the 5 km maps.

It should also be noted that for NH_3, exceedance of the critical load for N tends to occur before exceedance of the critical level. This is because of the rapid dry deposition rate for NH_3, which means that (with other nitrogen inputs at typical rates), concentrations above 3-4 g m^{-3} would almost certainly result in deposition exceeding critical loads.

7.4 Ozone (O_3)

Concentrations of ozone, unlike those of SO_2 and NO_x are large throughout Scotland and the largest values occur in rural areas because the emissions of NO_x in urban areas deplete O_3 by gas phase reactions (PORG, 1993). However, with current understanding of the subject concentrations smaller than 40 ppb (by volume) are not considered to be damaging. The mean O_3 concentrations throughout Scotland range from 10 to 30 ppb, with the largest values on the windy, exposed areas in the North and West in the uplands and also on the Isles (Figure 44). It should be noted, however, that the concentration field for ozone is based on few monitoring stations, there being only three rural sites in southern Scotland (Penicuik, Dunslair Heights and Eskdalemuir), and one in the north, at Strath Vaich. There are substantial year-to-year variations in the concentrations which are generally smoothed by considering a 5 year average, as in Figure 44. The smallest concentrations occur in the sheltered lowlands and close to urban centres. It is notable that Scotland is subject to the largest mean O_3 concentrations in the UK due to the windy climate, which mixes down ozone to the surface from higher levels in the boundary layer, and reduces the surface concentration by dry deposition. The ozone concentrations observed in Scotland are dominated by the mid-latitude background concentrations, which in the long term (20 to 60 years) are expected to rise significantly. This is a consequence of increasing emissions of volatile organic compounds and NO_x throughout the mid-latitudes of the northern hemisphere, and of the effects of warming of the troposphere.

Using the AOT40 values (outlined in paragraph 2.4) and the O_3 monitoring data for Scotland, maps have been produced for crops and semi-natural vegetation (Figure 45), and for forests (Figure 46). Exceedances are observed for crops and semi-natural vegetation (Figure 47). The map shows that 49% of Scotland exceeds this critical level, provided that this vegetation type is present in these grid squares. Among the critical levels maps therefore, the O_3 exceedances are the largest. It is important to note in a wider context that the exceedances in Scotland are much smaller than those elsewhere in the UK and in Continental Europe. The smaller exceedances of 40 ppb in Scotland are the consequence of a reduced frequency of polluted air from the main emission areas of the UK and continental Europe, and of the generally lower temperatures and solar radiation levels required for the photochemical reactions which generate additional ozone.

8. POLLUTANT DEPOSITION AND GASEOUS POLLUTANTS ON SPECIES OF CONSERVATION INTEREST

Calluna vulgaris, Drosera rotundifolia, Racomitrium lanuginosum and *Primula* spp. were selected as examples of species of conservation importance that may be currently affected by air pollution. Maps of exceedances of critical loads and levels in relation to the distribution of these species are described below.

Figure 48 shows the distribution of critical loads exceedance for nutrient nitrogen overlain on the distribution of *Calluna vulgaris* for all recorded occurrences (pre- and post-1950 records). The critical load is estimated to be exceeded over nearly all of the south and eastern half of Scotland. The largest exceedances occur in areas of high wet deposition and lowland agricultural areas. This map obviously has important implications, but it should be noted that it reflects predicted rather than actual measured detrimental effects.

Figure 49 shows the estimated distribution of critical load exceedance for nutrient nitrogen overlain with the pre- and post-1950 distribution of *Drosera rotundifolia*. Here the level of exceedance is rather higher than for *Calluna vulgaris* with many areas in excess of 10 kg ha^{-1} yr^{-1} exceedance.
An example map for exceedance of the SO_2 critical level is shown in Figure 50 for *Racomitrium lanuginosum*. Although the critical level is not exceeded in any location where *R. lanuginosum* has been recorded, a substantial area in central Scotland exceeds 25% of the critical level.

Ozone maps are provided for each of these four species (Figures 51-54). Exceedance is largest in the high altitude area of the Grampian mountains. Hence species favouring high altitudes, such as *C. vulgaris* and *R. lanuginosum*, are potentially most at risk from O_3.

9 CONCLUSIONS

- **Critical loads - acidification**: substantial areas of Scotland remain in exceedance of critical loads, although sulphur deposition is declining and recovery in some areas may be expected with the current international protocols.

  However, nitrogen is becoming the major contributor to acidification and the cause of critical loads exceedances, and the underpinning science to quantify the role of N in acidification is substantially weaker than that for sulphur.

- **Critical loads - eutrophication**: large areas of semi-natural vegetation and important habitats for conservation are currently subject to N deposition substantially in excess of critical loads and little in current protocols will reduce these exceedances in the coming decade.

- **Critical levels - primary pollutants:** exceedance of critical levels for SO_2, NH_3 and NO_x represents only a minor problem for SNH, as areas of exceedance are small, and in the case of sulphur declining. By contrast, these primary pollutants still contribute significantly to exceedance of critical loads.

- **Critical levels - ozone**: in contrast to the primary pollutants, the terrestrial exposure to ozone shows widespread critical level exceedance for semi-natural vegetation, particularly in the uplands.

- **Habitats and Species:** the first maps of critical load and level exceedance for habitats and species in Scotland have been constructed. These provide a focused picture of where damage may be occurring from air pollution in relation to nature conservation concerns.

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APPENDIX - LIST OF MAPS

1. Total Acid Deposition 1995-97 including. NH_x
2. Total Acid Deposition 1995-97 excluding NH_x
3. Total N Deposition 1995-97 Scotland - all vegetation types
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19. Exceedance of critical loads of acidity for acid grassland
20. Exceedance of critical loads of acidity for heathland
21. Exceedance of critical loads of nutrient N for acid grassland
22. Exceedance of critical loads of nutrient N for calcareous grassland
23. Exceedance of critical loads of nutrient N for peatland
24. Exceedance of critical loads of nutrient N for heathland
25. Exceedance of critical loads of nutrient N for coniferous woodland
26. Exceedance of critical loads of nutrient N for deciduous woodland
27. Exceedance of critical loads of nutrient N for oligotrophic waters
28. SO_2 concentrations 1962/63 to 1990 from urban and rural monitoring/modelled data
29. SO_2 concentrations & BRC spatial distribution of *Antitrichia curtipendula*
30. SO_2 concentrations & BRC spatial distribution of *Cryphaea heteromalla*
31. SO_2 concentrations & BRC spatial distribution of *Grimmia orbiculare*
32. SO_2 concentrations & BRC spatial distribution of *Leucodon sciuroides*
33. SO_2 concentrations & BRC spatial distribution of *Orthotrichium speciosum*
34. SO_2 concentrations & BRC spatial distribution of *Ulota coarctata*
35. SO_2 concentrations & BRC spatial distribution of *Ulota hutchiensiae*
36. SO_2 concentrations 1996
37. SO_2 - proportion of critical level (%) and exceeded areas for crops
38. SO_2 - proportion of critical level (%) and exceeded areas for forests and semi-natural vegetation
39. SO_2 - proportion of critical level (%) and exceeded areas for cyano-bacterial lichens
40. NO_x concentrations (g m^{-3})
41. NO_x - proportion of critical level (%) and exceeded areas for all habitats 1996

Figure 1. Total Acid Deposition 1995-97

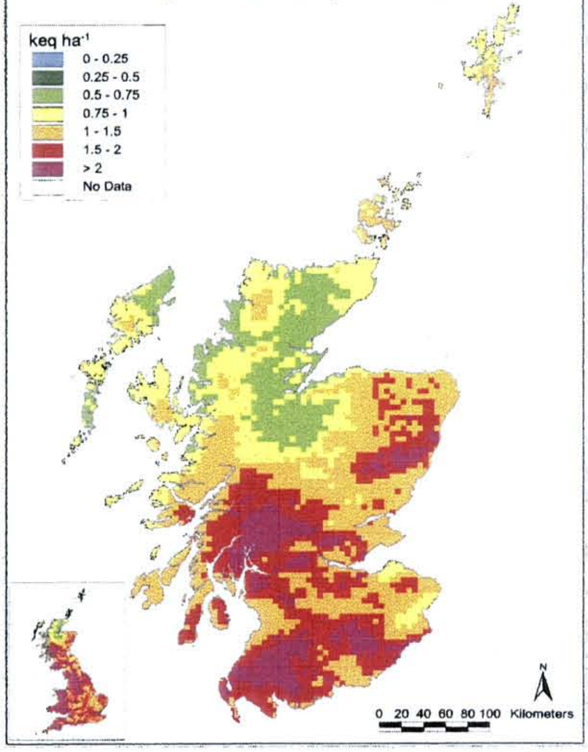


Figure 2. Total Acid Deposition (excluding NH_x) 1995-97

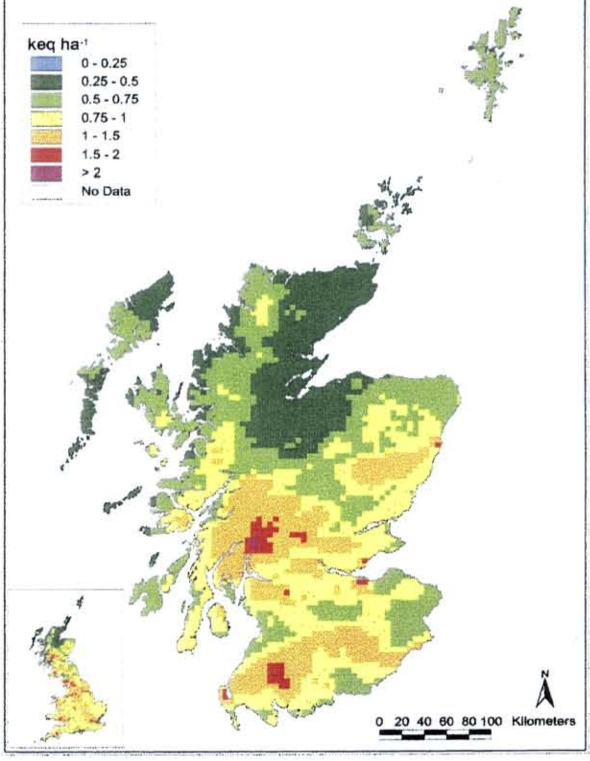


Figure 3. Nitrogen Deposition 1995-97
All vegetation types

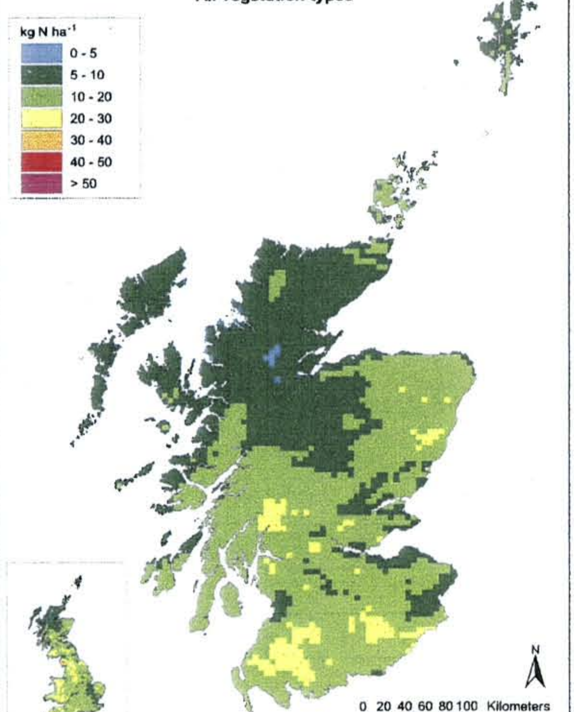


Figure 4. Nitrogen Deposition 1995-97
Woodland

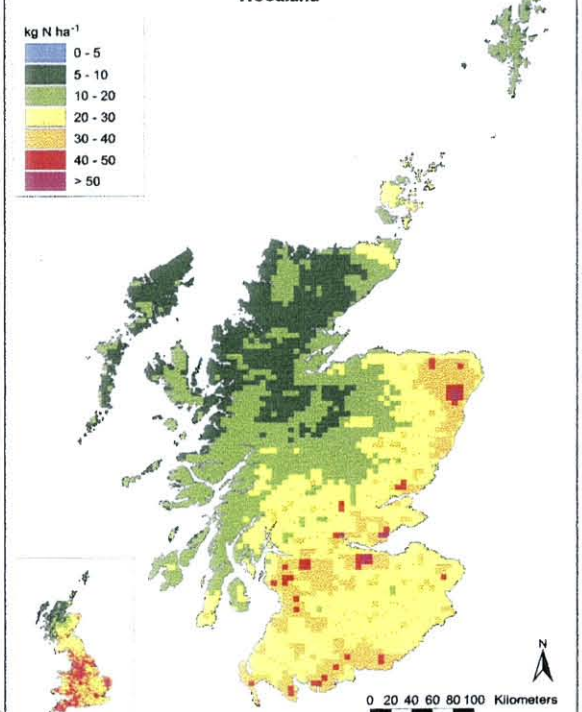


Figure 5. Nitrogen Deposition 1995-97
Heathland and Rough Grazing

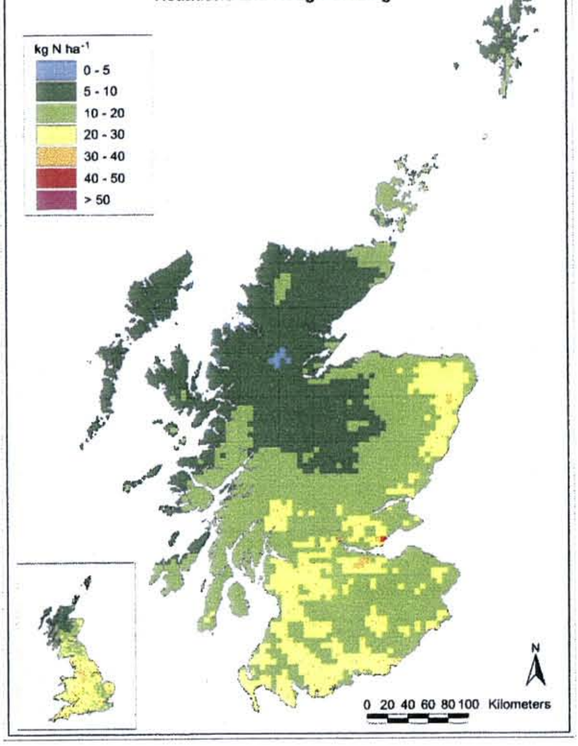


Figure 6. Empirical Critical Loads of Acidity for Soils

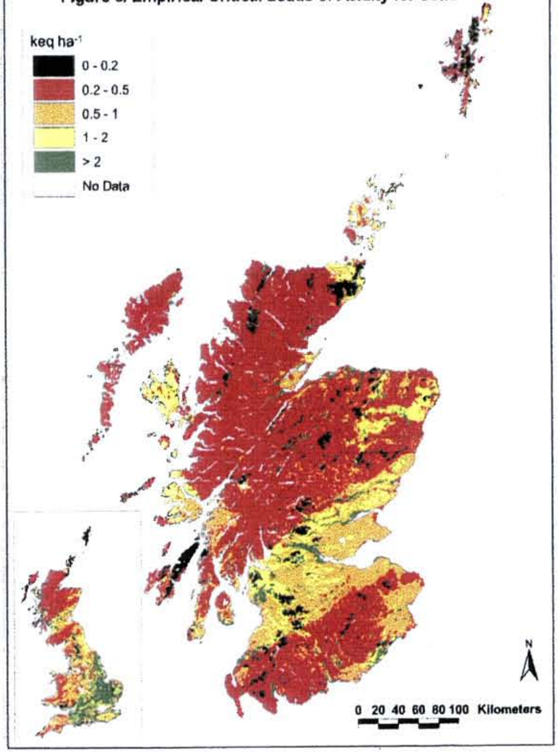


Figure 7. Critical Loads of Acidity for Heathland

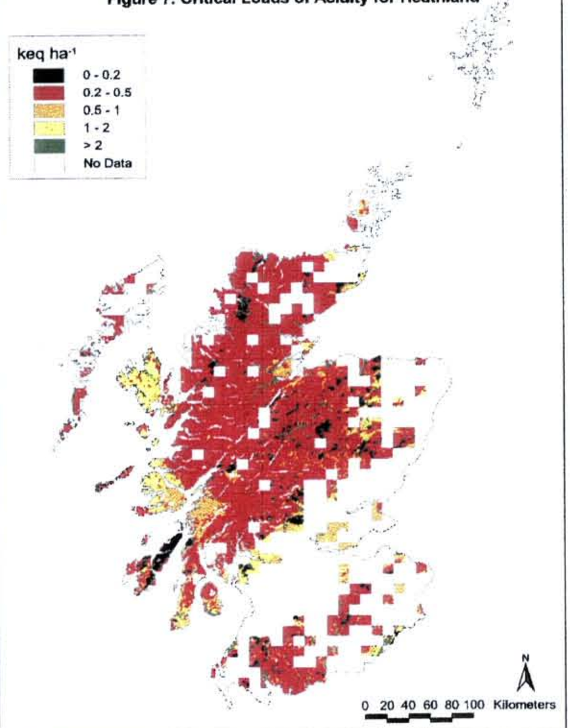
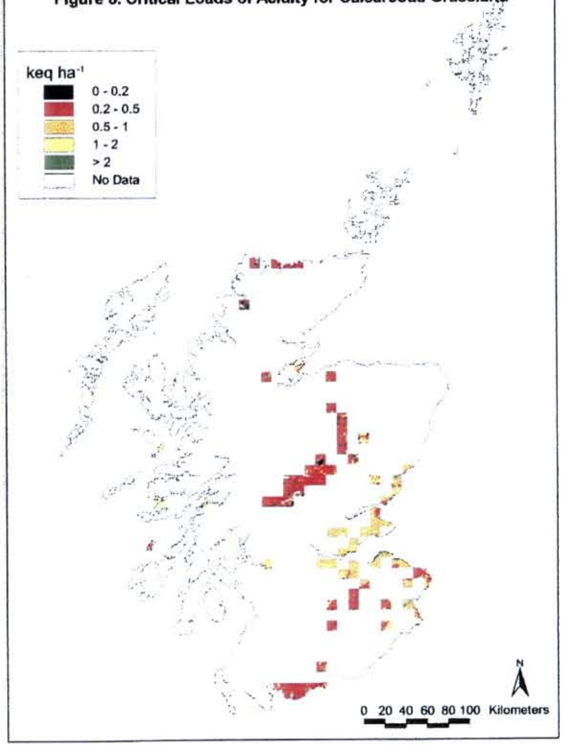


Figure 8. Critical Loads of Acidity for Calcareous Grassland



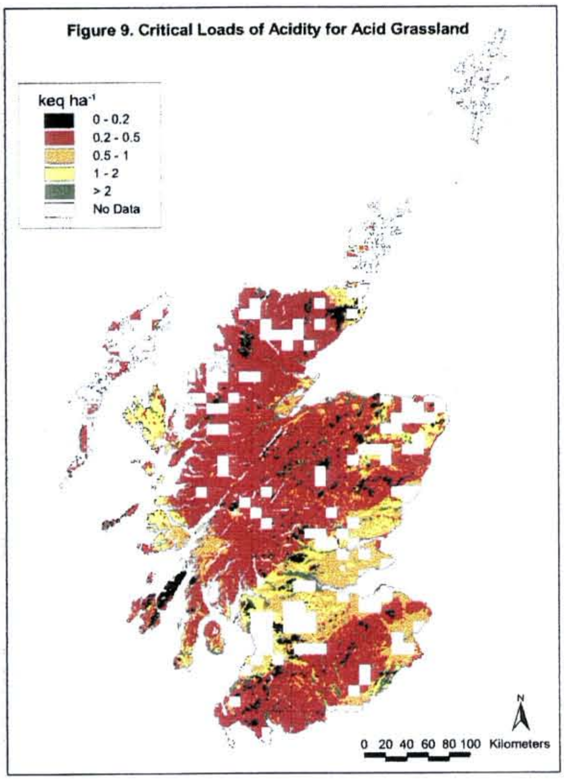


Figure 9. Critical Loads of Acidity for Acid Grassland

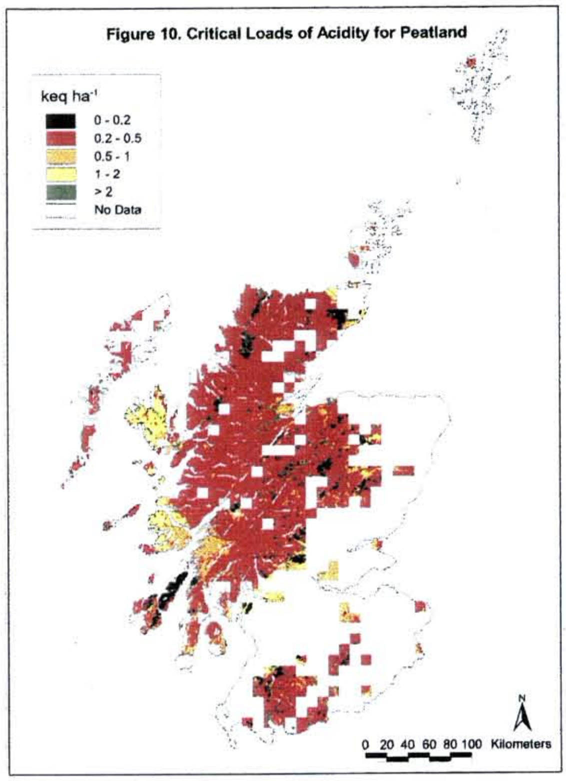


Figure 10. Critical Loads of Acidity for Peatland

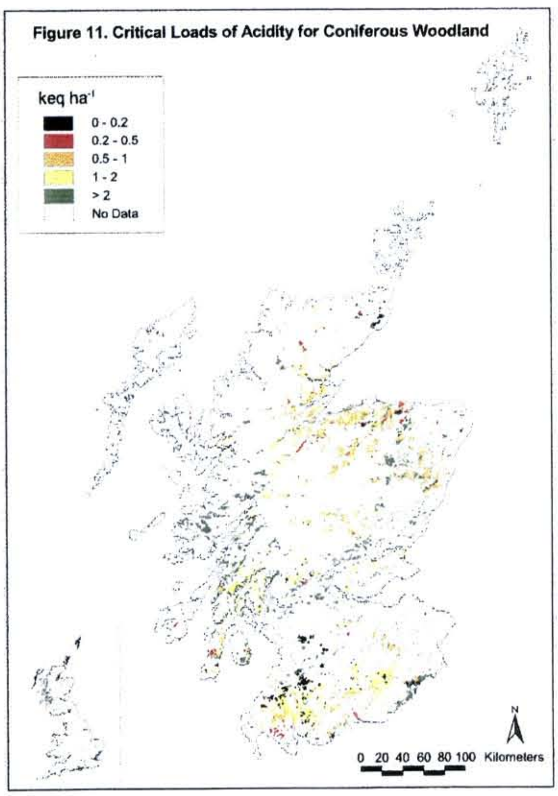


Figure 11. Critical Loads of Acidity for Coniferous Woodland

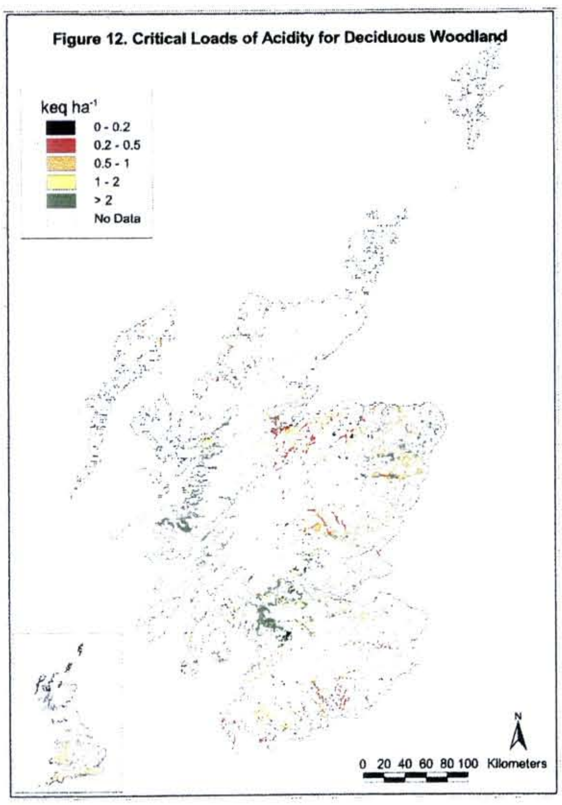


Figure 12. Critical Loads of Acidity for Deciduous Woodland

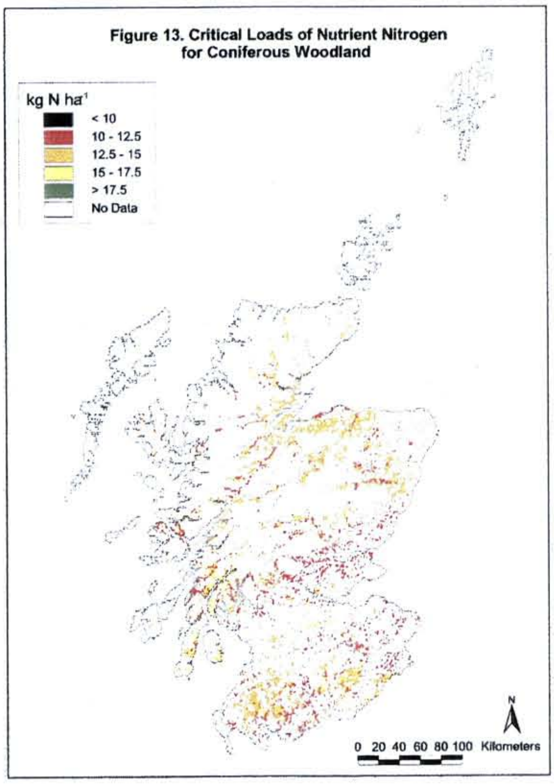


Figure 13. Critical Loads of Nutrient Nitrogen for Coniferous Woodland
kg N ha-1
< 10
10 - 12.5
12.5 - 15
15 - 17.5
> 17.5
No Data
N
0 20 40 60 80 100 Kilometers

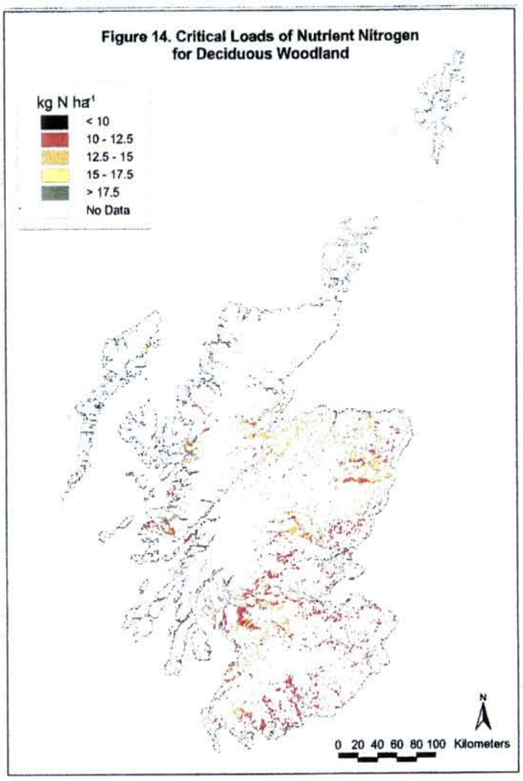


Figure 14. Critical Loads of Nutrient Nitrogen for Deciduous Woodland
kg N ha-1
< 10
10 - 12.5
12.5 - 15
15 - 17.5
> 17.5
No Data
N
0 20 40 60 80 100 Kilometers

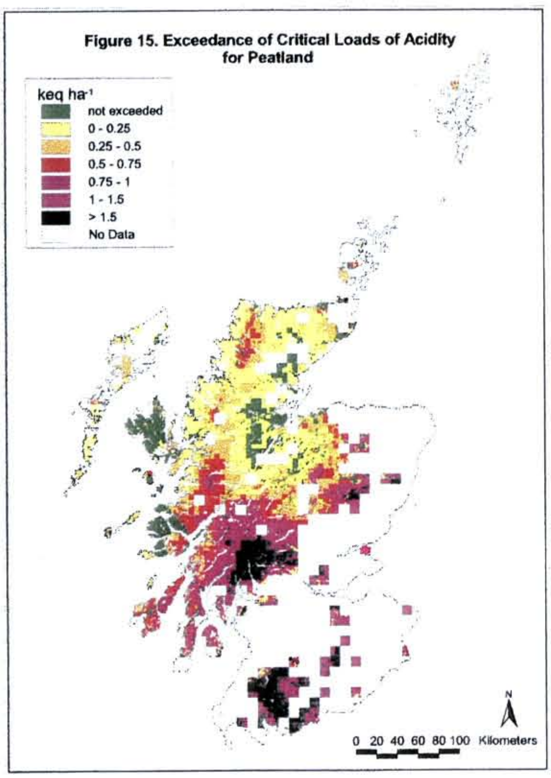


Figure 15. Exceedance of Critical Loads of Acidity for Peatland
keq ha-1
not exceeded
0 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
> 1.5
No Data
N
0 20 40 60 80 100 Kilometers

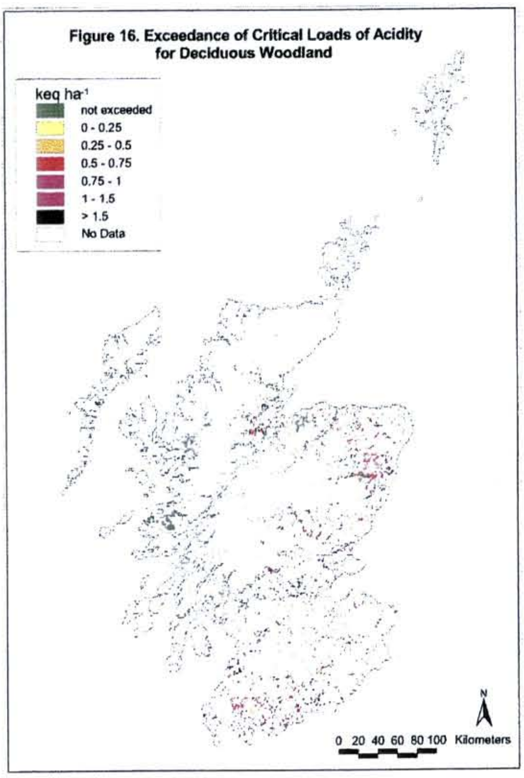


Figure 16. Exceedance of Critical Loads of Acidity for Deciduous Woodland
keq ha-1
not exceeded
0 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
> 1.5
No Data
N
0 20 40 60 80 100 Kilometers

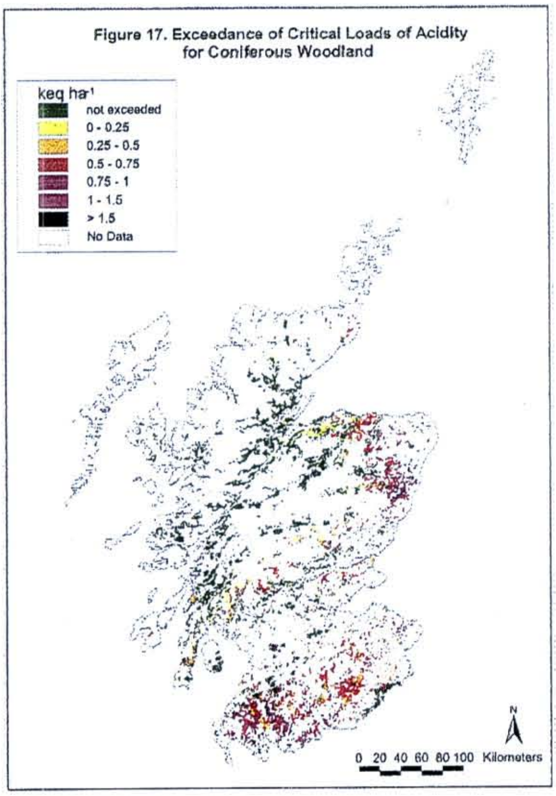


Figure 17. Exceedance of Critical Loads of Acidity for Coniferous Woodland

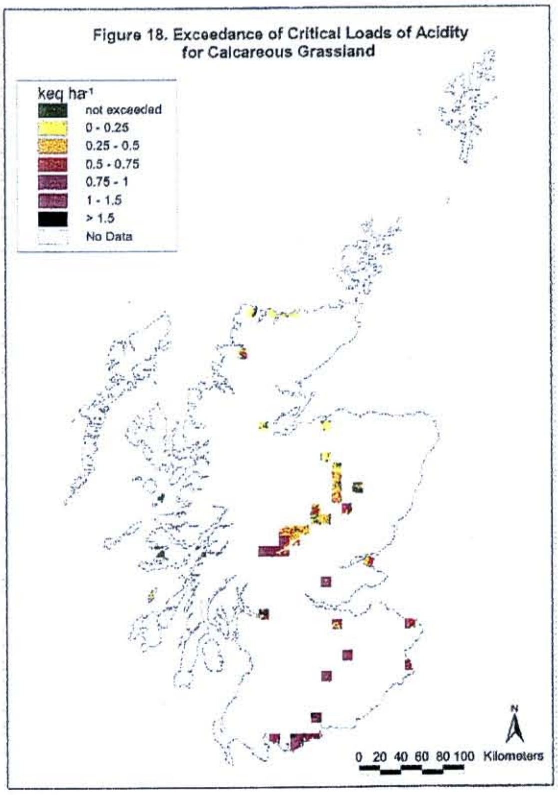


Figure 18. Exceedance of Critical Loads of Acidity for Calcareous Grassland

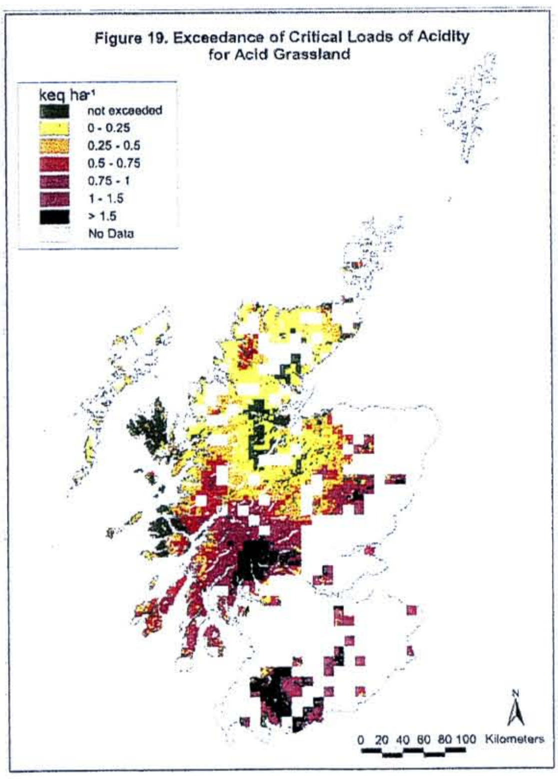


Figure 19. Exceedance of Critical Loads of Acidity for Acid Grassland

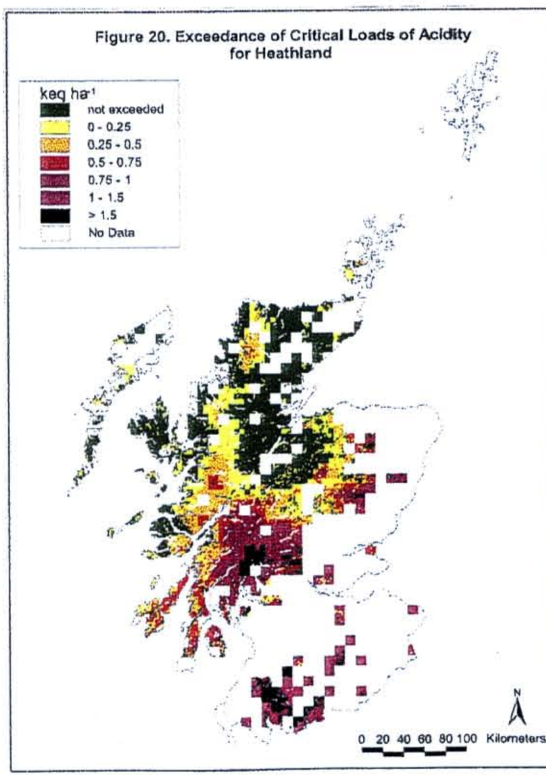


Figure 20. Exceedance of Critical Loads of Acidity for Heathland

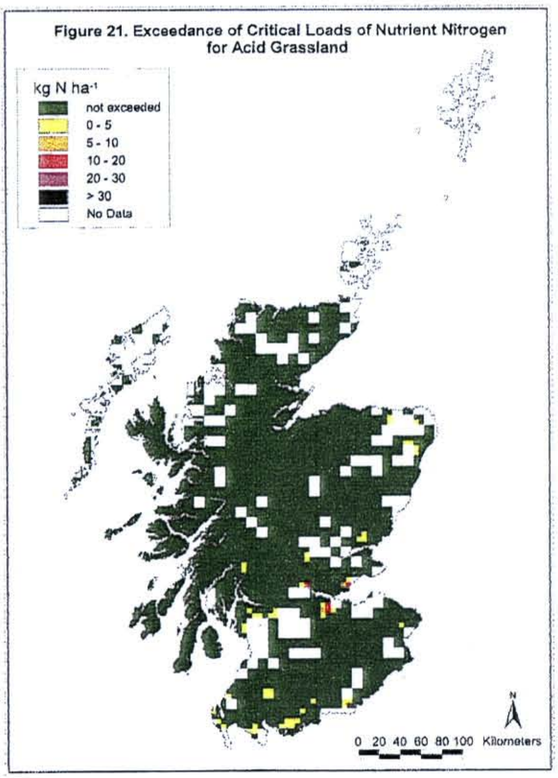


Figure 21. Exceedance of Critical Loads of Nutrient Nitrogen for Acid Grassland
kg N ha-1
not exceeded
0 - 5
5 - 10
10 - 20
20 - 30
> 30
No Data
N
0 20 40 60 80 100 Kilometers

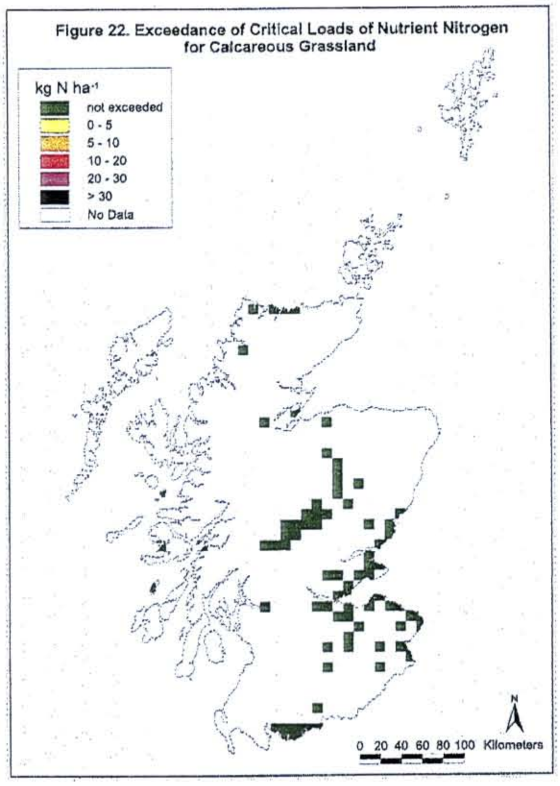


Figure 22. Exceedance of Critical Loads of Nutrient Nitrogen for Calcareous Grassland
kg N ha-1
not exceeded
0 - 5
5 - 10
10 - 20
20 - 30
> 30
No Data
N
0 20 40 60 80 100 Kilometers

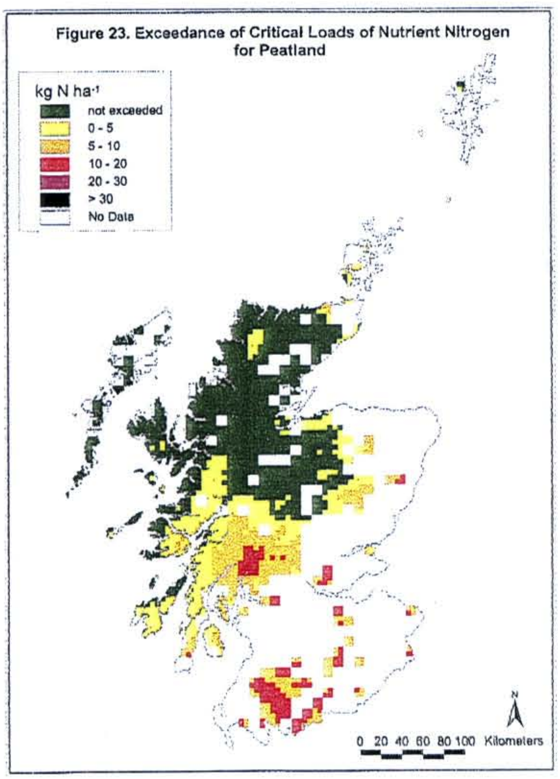


Figure 23. Exceedance of Critical Loads of Nutrient Nitrogen for Peatland
kg N ha-1
not exceeded
0 - 5
5 - 10
10 - 20
20 - 30
> 30
No Data
N
0 20 40 60 80 100 Kilometers

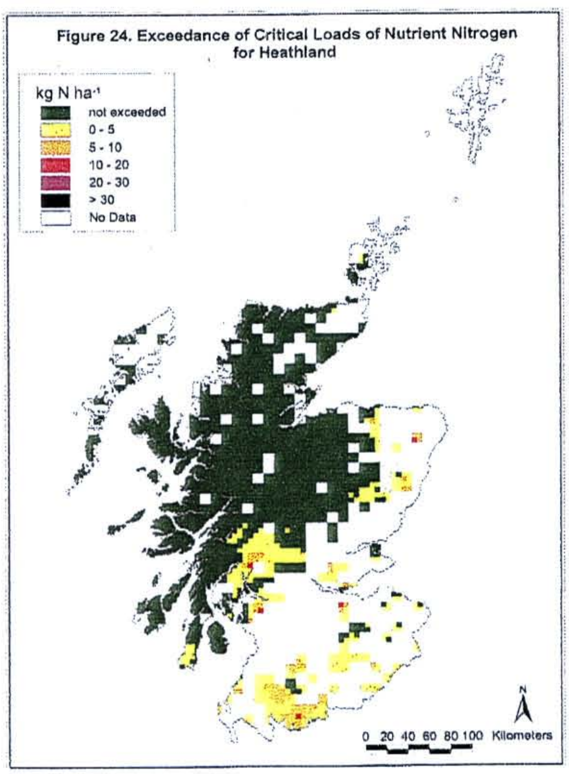


Figure 24. Exceedance of Critical Loads of Nutrient Nitrogen for Heathland
kg N ha-1
not exceeded
0 - 5
5 - 10
10 - 20
20 - 30
> 30
No Data
N
0 20 40 60 80 100 Kilometers

Figure 25. Exceedance of Critical Loads of Nutrient Nitrogen for Coniferous Woodland

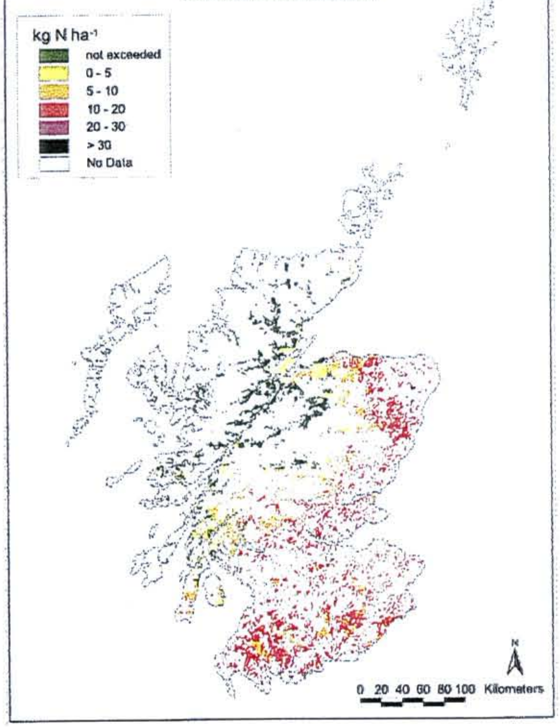


Figure 26. Exceedance of Critical Loads of Nutrient Nitrogen for Deciduous Woodland

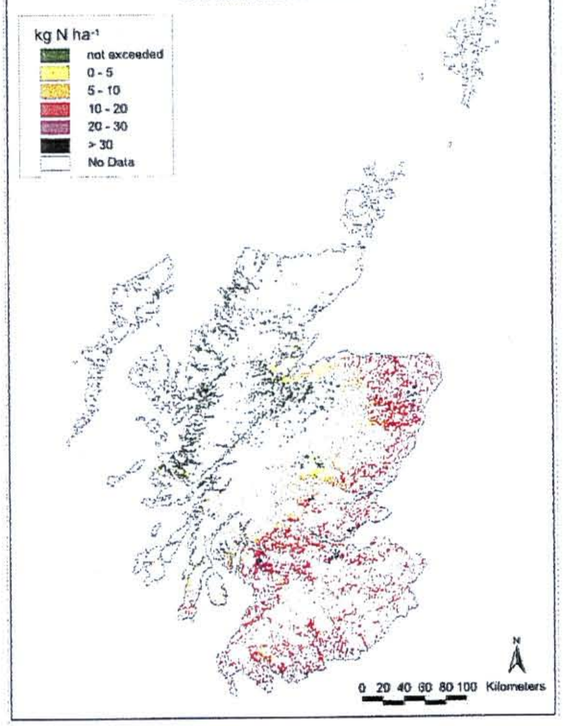


Figure 27. Exceedance of Critical Loads of Nutrient Nitrogen for Oligotrophic Waters

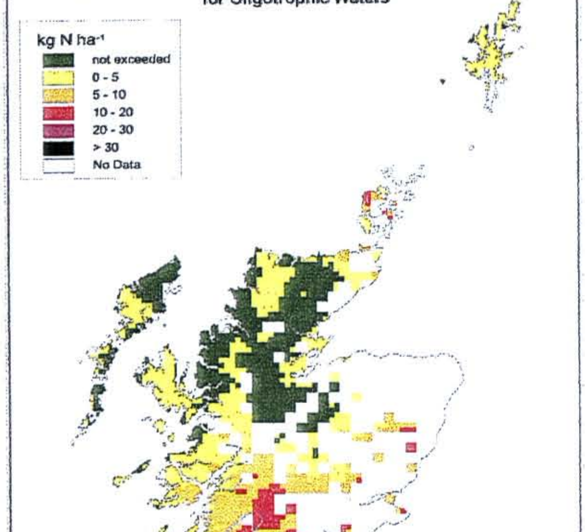


Figure 28. SO_2 concentrations (urban + rural)

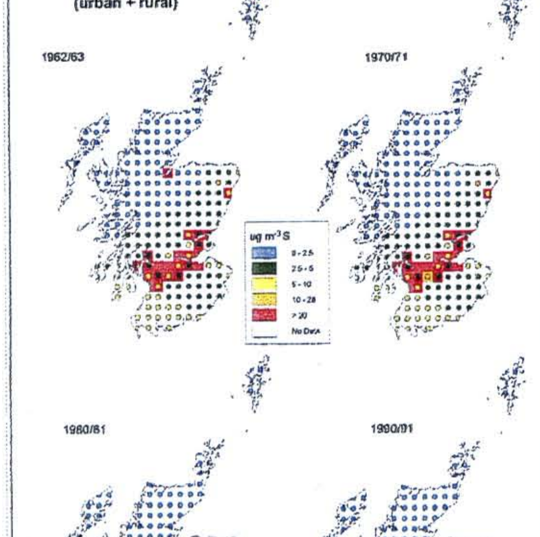


Figure 29. Distribution of Antitrichia curtipendula & SO_2 concentrations

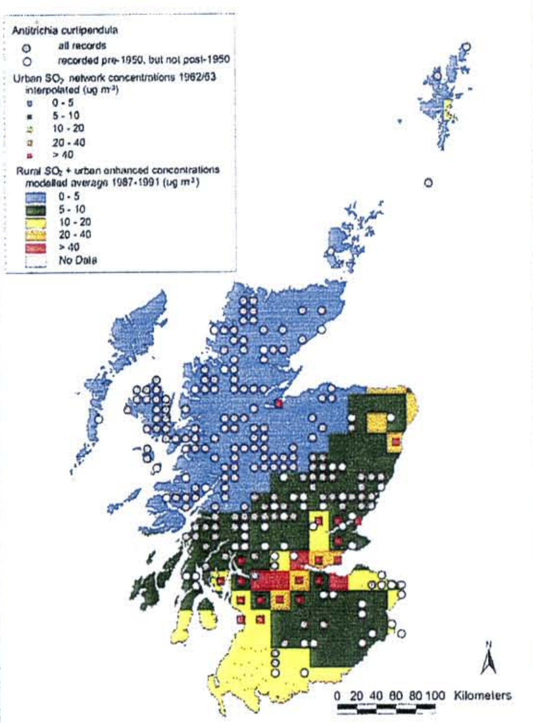


Figure 30. Distribution of Cryphaea heteromalla & SO_2 concentrations

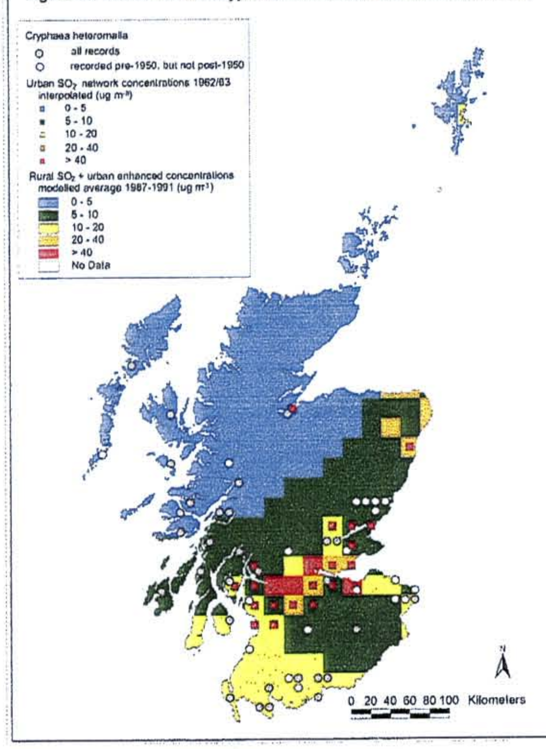


Figure 31. Distribution of Grimmia orbiculare & SO_2 concentrations

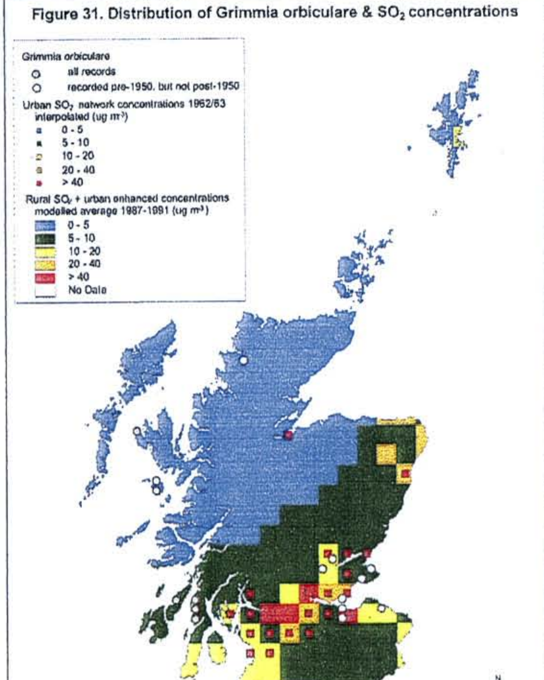


Figure 32. Distribution of Leucodon sciuroides & SO_2 concentrations

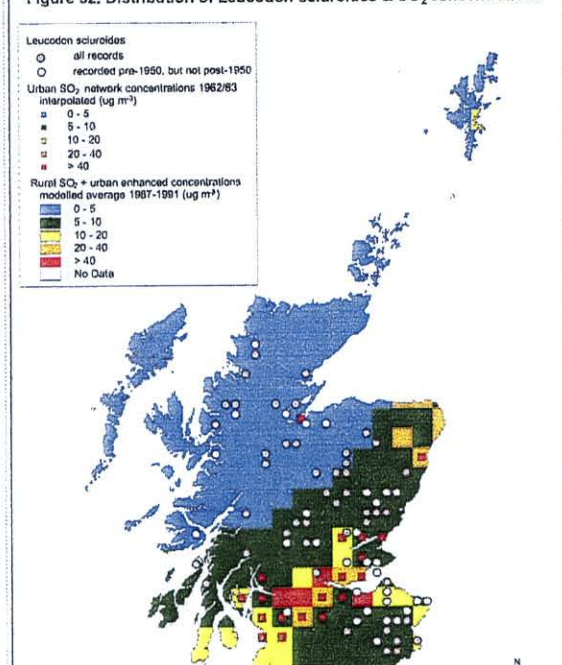


Figure 33. Distribution of Orthotrichium speciosum & SO_2 concentrations

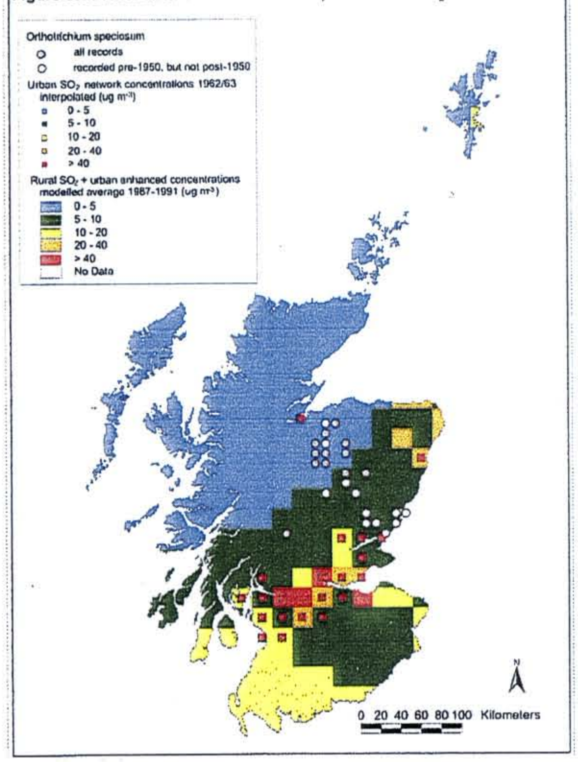


Figure 34. Distribution of Ulota coarctata & SO_2 concentrations

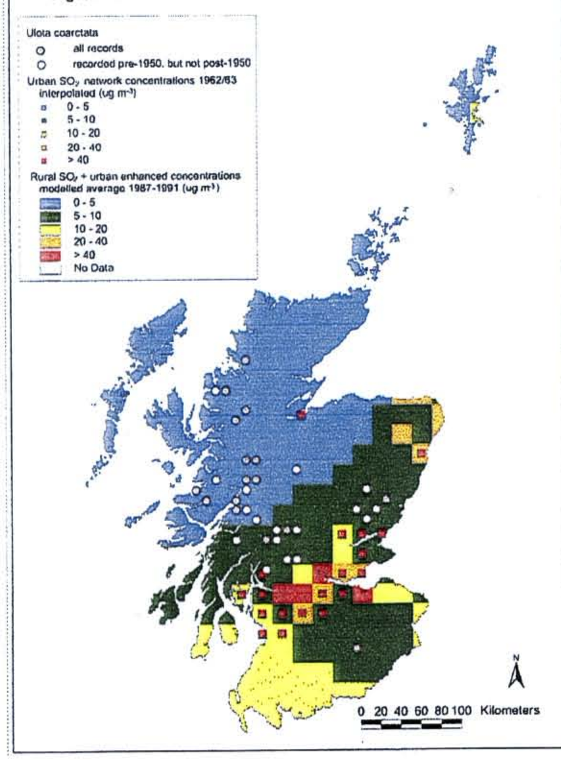


Figure 35. Distribution of Ulota hutchinsiae & SO_2 concentrations

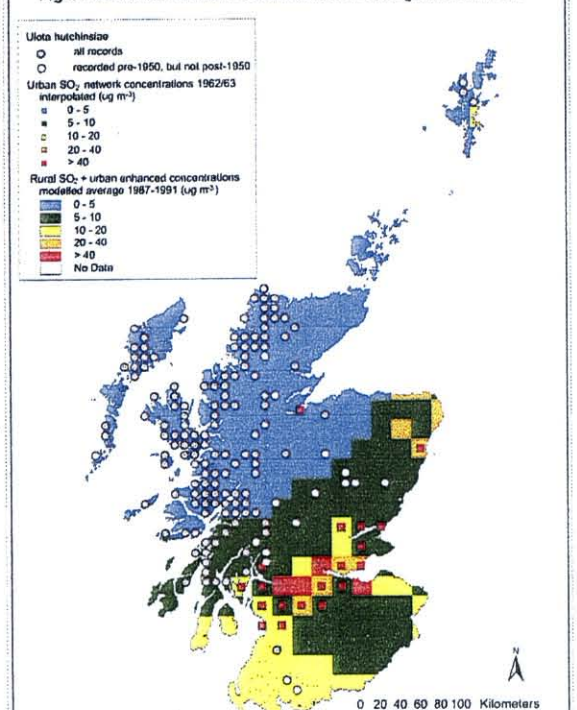


Figure 36. Sulphur Dioxide Concentrations 1996

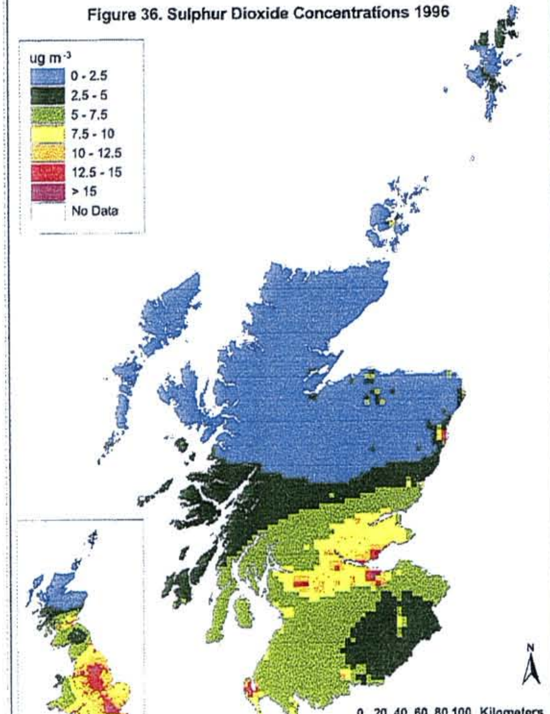


Figure 37. SO_2 Concentrations - Proportion of Critical Level (%) and exceeded areas (> 30 ug m^{-3}) for crops 1996

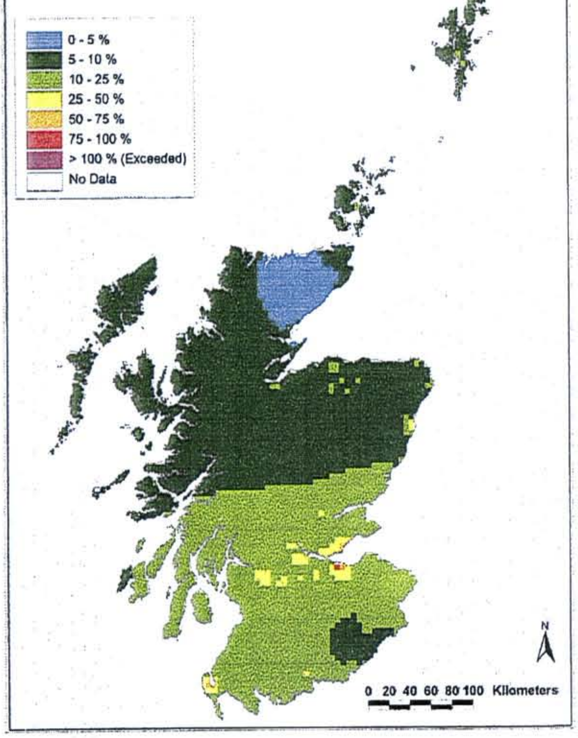


Figure 38. SO_2 Concentrations - Proportion of Critical Level (%) and exceeded areas (> 20 ug m^{-3}) for forests & semi-natural vegetation 1996

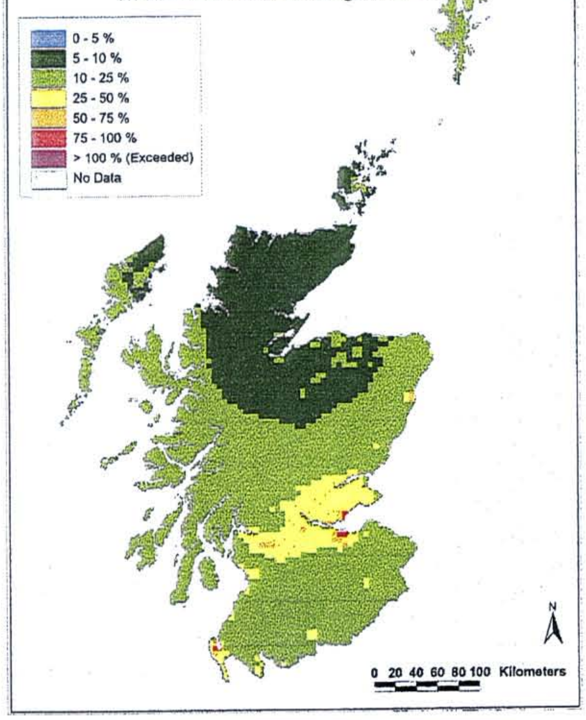


Figure 39. SO_2 Concentrations - Proportion of Critical Level (%) and exceeded areas (> 10 ug m^{-3}) for cyanobacterial lichens 1996

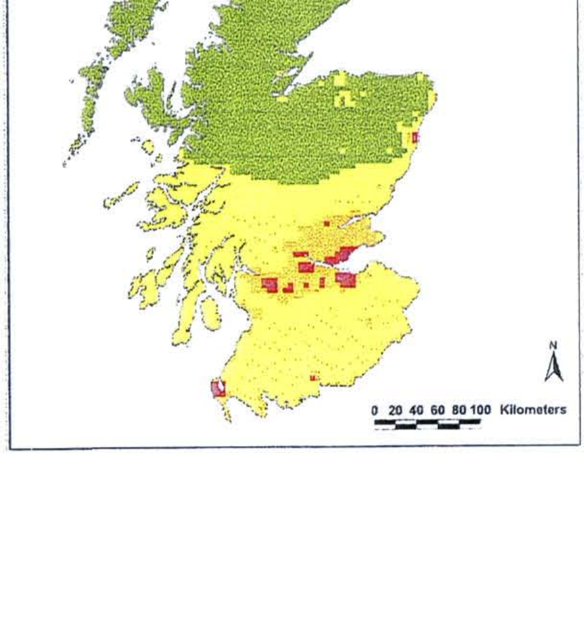


Figure 40. NO_x Concentrations 1996

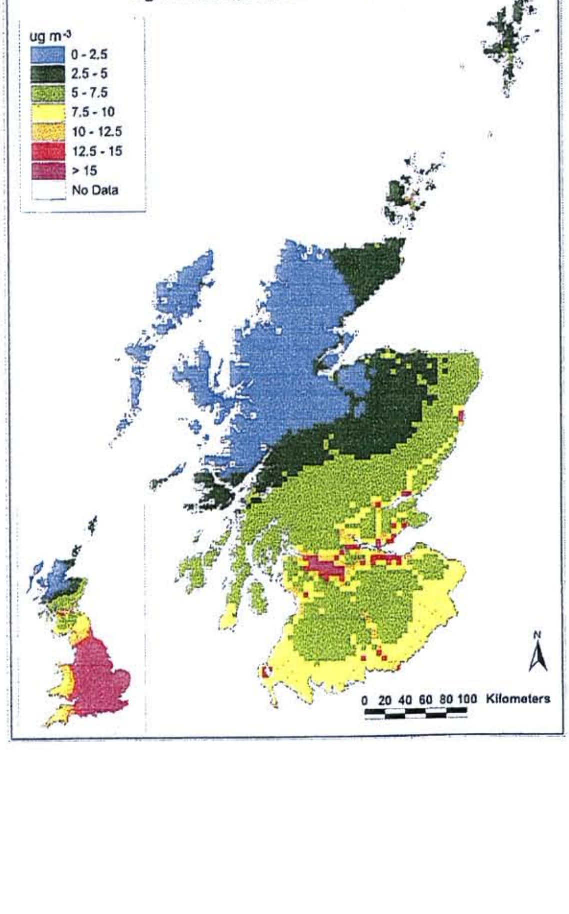


Figure 41. NO_x Concentrations - Proportion of Critical Level (%) and exceeded areas (> 30 ug m^{-3}) for all habitats 1996

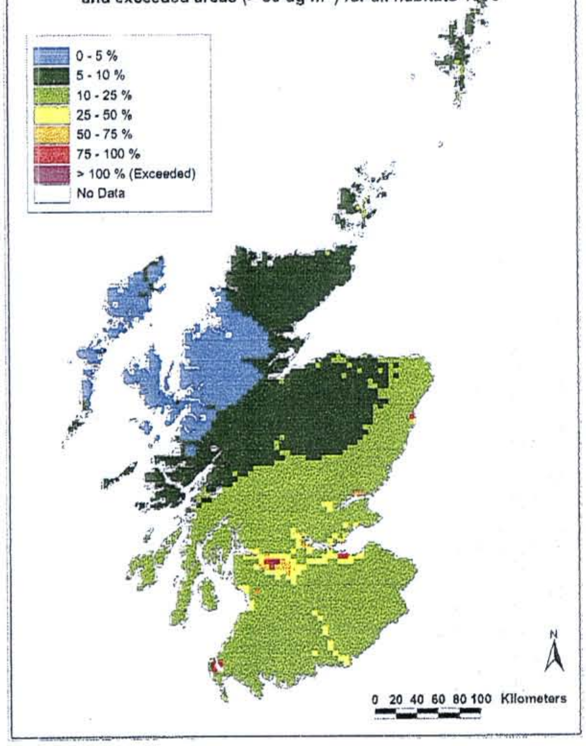


Figure 42. Ammonia Concentrations 1996

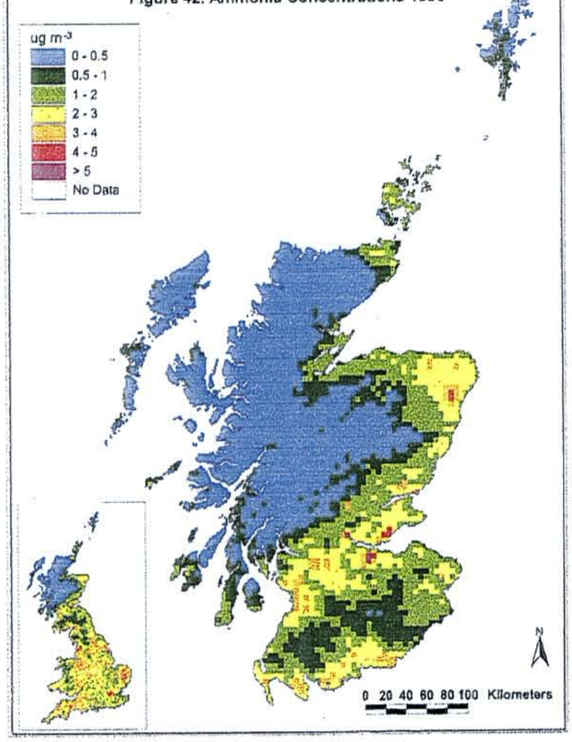


Figure 43. NH_3 Concentrations - Proportion of Critical Level (8 ug m^{-3}) for all habitats (%) 1996

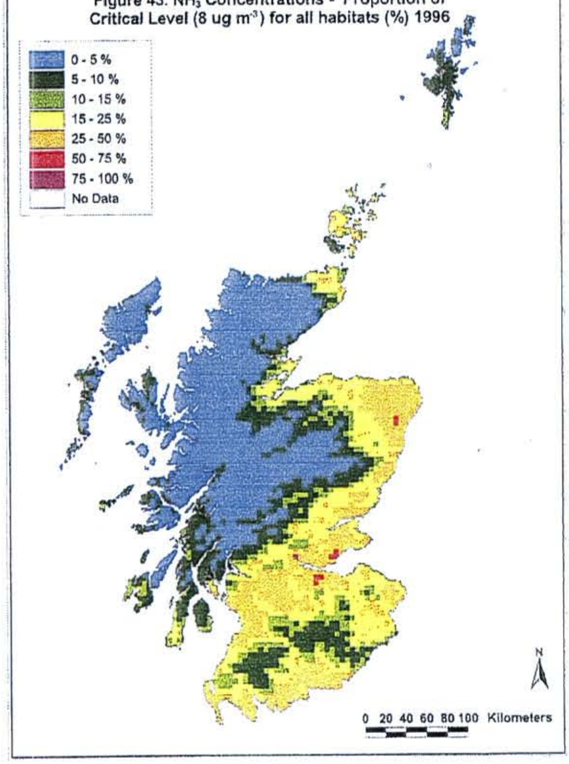


Figure 44. Ozone - Mean Annual Concentrations Average 1992 - 1996

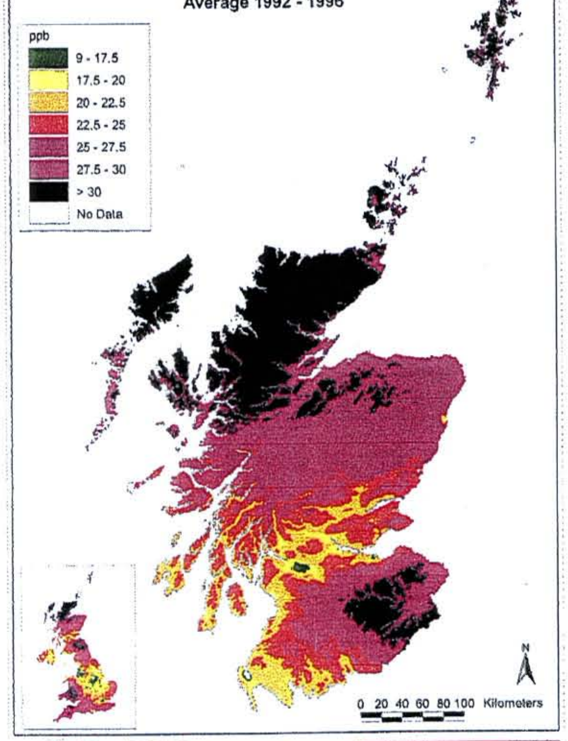


Figure 45. Ozone - AOT40 Crops & Semi-natural Ecosystems 1992-96

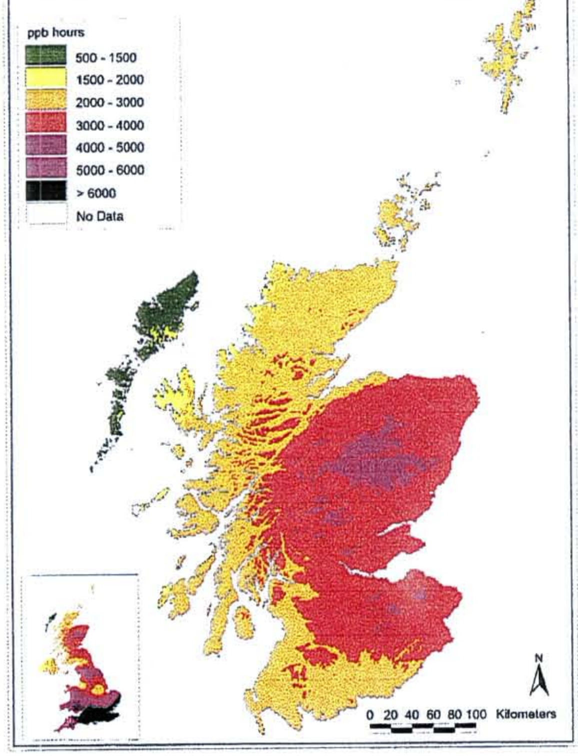


Figure 46. Ozone - AOT40 Forests 1992-1996

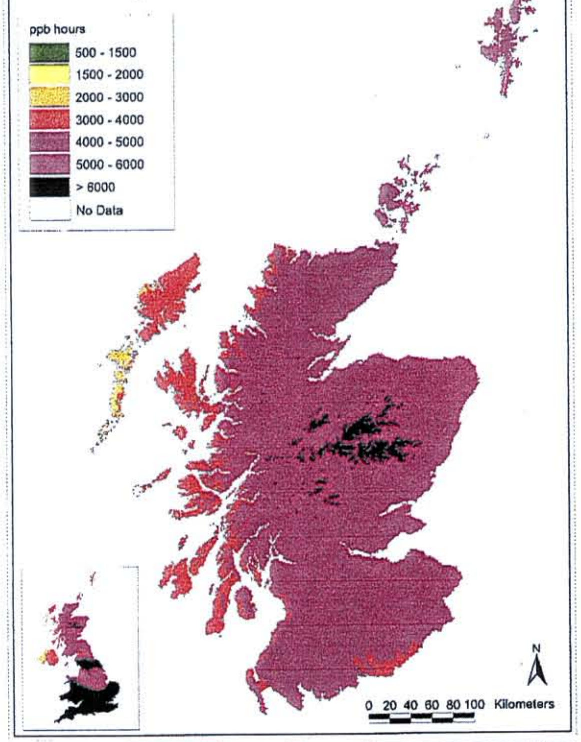


Figure 47. Ozone - Exceedance of Critical Level for Crops & Semi-natural Ecosystems 1992-1996 (AOT40 >3000 ppb hours)

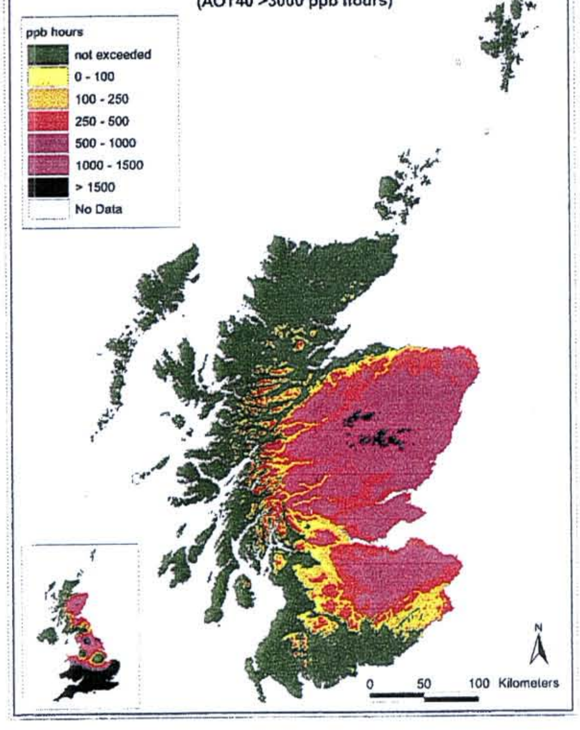


Figure 48. Nutrient N Critical Loads Exceedance Calluna vulgaris (>15 kg N ha^{-1})

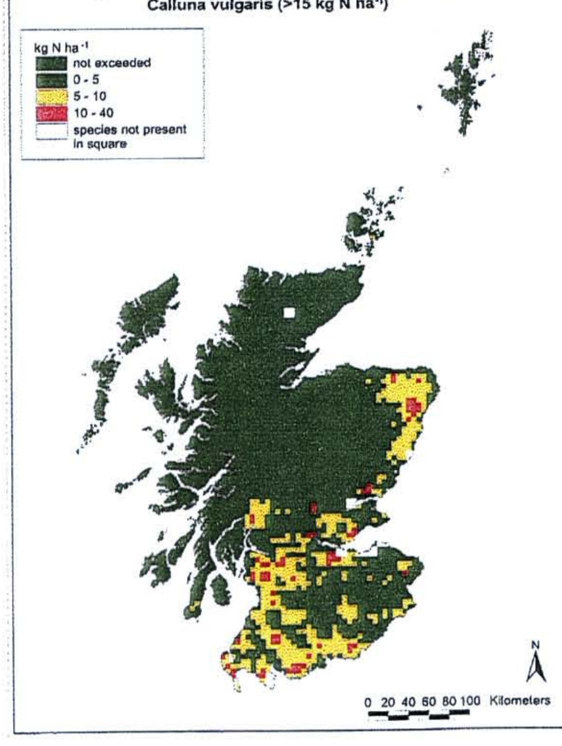


Figure 49. Nutrient N Critical Loads Exceedance
Drosera rotundifolia (>10 kg N ha^{-1})

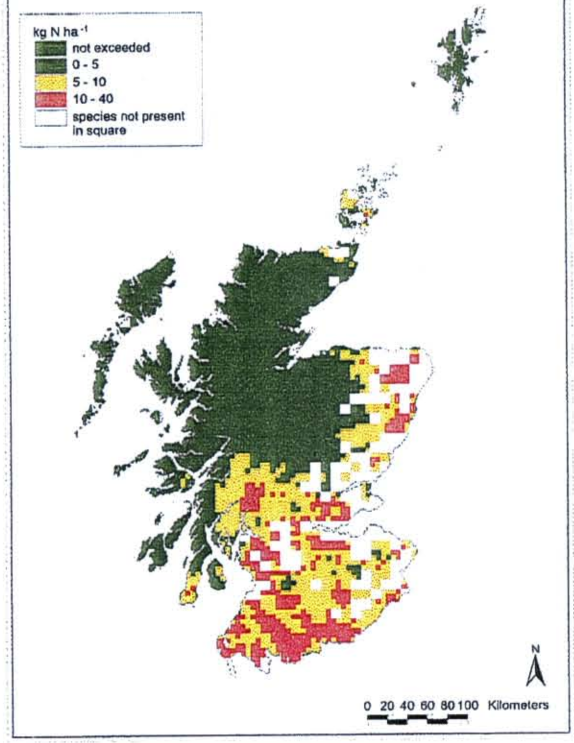


Figure 50. SO_2 concentrations - Proportion of Critical Level (20 ug m^{-3}) for forests & semi-natural systems 1996
Racomitrium lanuginosum

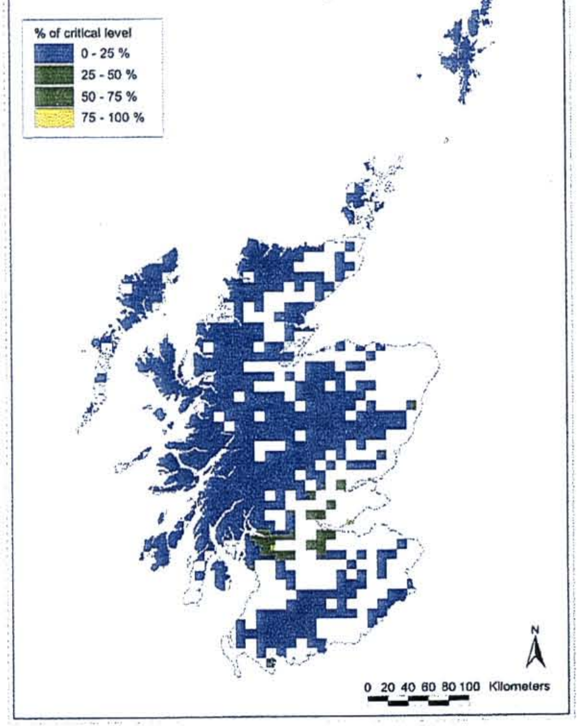


Figure 51. Ozone - AOT40 Exceedance
(Crops & Semi-natural systems)
Calluna vulgaris

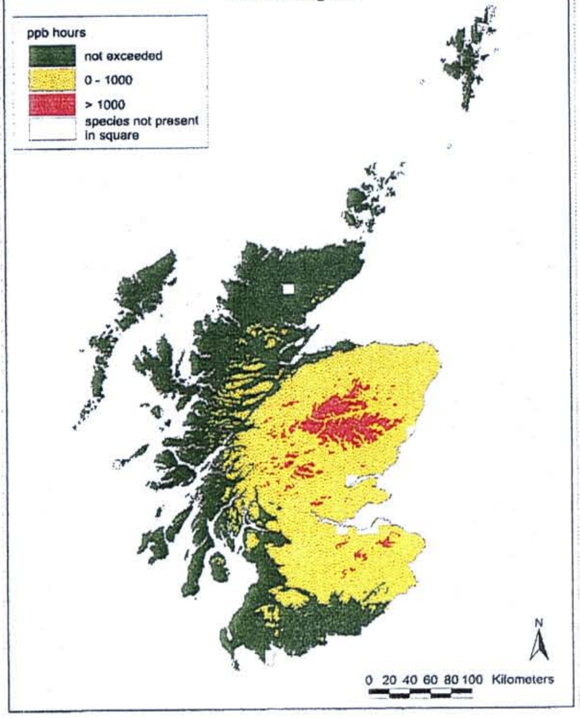
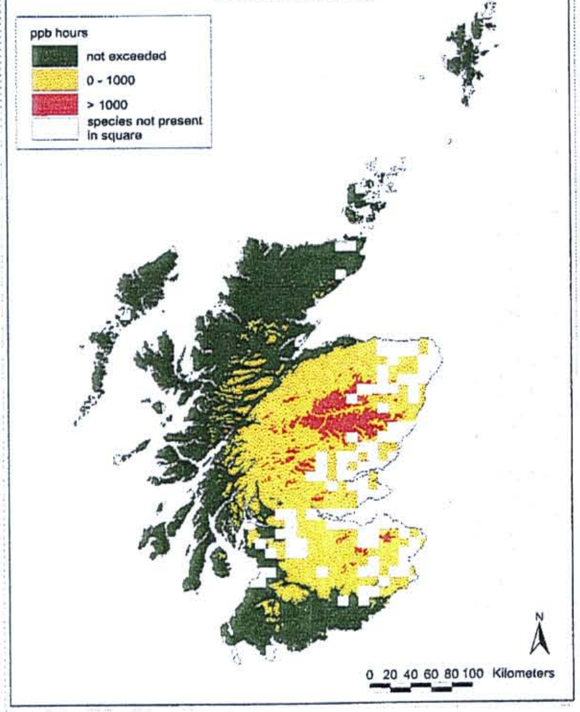


Figure 52. Ozone - AOT40 Exceedance
(Crops & Semi-natural systems)
Drosera rotundifolia



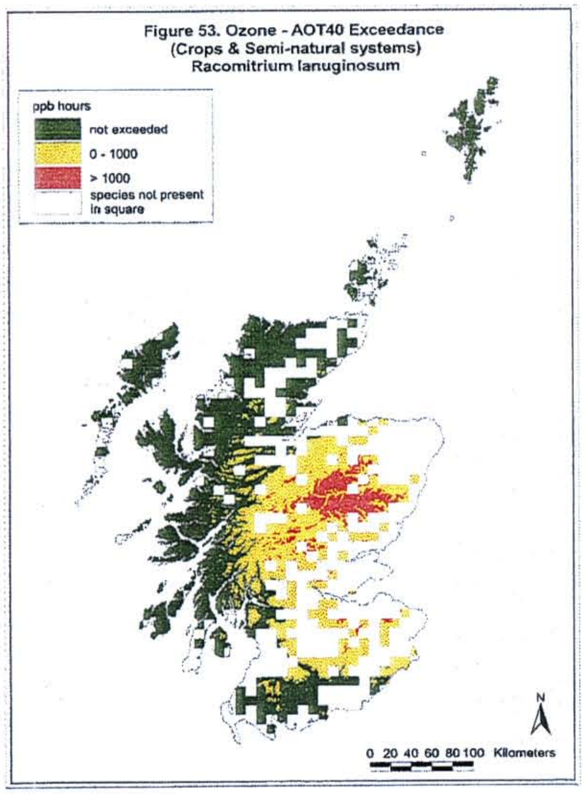


Figure 53. Ozone - AOT40 Exceedance
(Crops & Semi-natural systems)
Racomitrium lanuginosum
ppb hours
not exceeded
0 - 1000
> 1000
species not present
in square
N
0 20 40 60 80 100 Kilometers

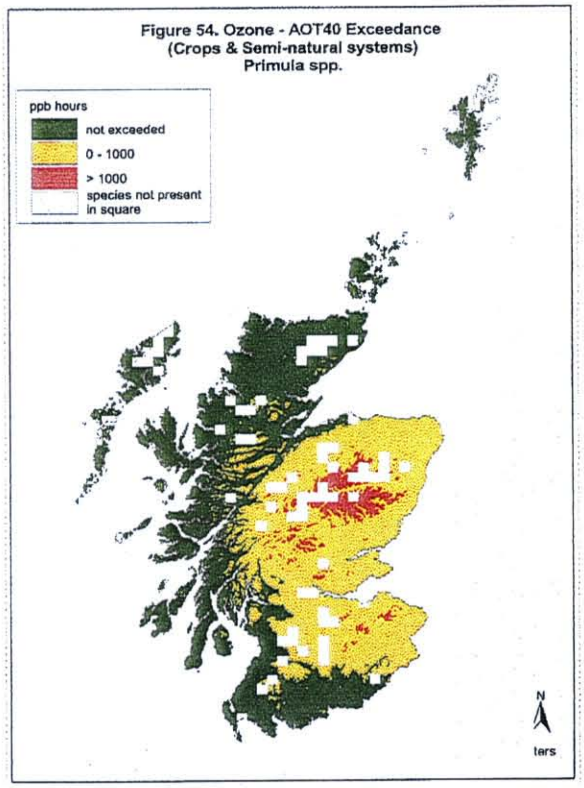


Figure 54. Ozone - AOT40 Exceedance
(Crops & Semi-natural systems)
Primula spp.
ppb hours
not exceeded
0 - 1000
> 1000
species not present
in square
N
ters

Scottish Natural Heritage

Scottish Natural Heritage is an independent body established by Parliament in 1992, responsible to the Secretary of State for Scotland.

Our task is to secure the conservation and enhancement of Scotland's unique and precious natural heritage - the wildlife, the habitats, the landscapes and the seascapes - which has evolved through the long partnership between people and nature.

We advise on policies and promote projects that aim to improve the natural heritage and support its sustainable use.

Our aim is to help people to enjoy Scotland's natural heritage responsibly, understand it more fully and use it wisely so that it can be sustained for future generations.